# 15 COGNITIVE FACTORS

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The opening chapter of this book noted that the primary goal of using helmet-mounted displays (HMDs) is to increase individual and unit performance. To meet such a goal, there must be an accurate transfer of information from the HMD to the user; and this transfer must occur at appropriate times. Ideally, an HMD would be designed to accommodate the abilities and limitations of users' cognitive processes. It is not enough for the information to be displayed (visually, auditorially, or tactually); the information must be perceived, attended, remembered, and organized in a way that guides appropriate decision-making, judgment, and action.

Cognitive science emphasizes the scientific study of human cognition through empirical measurements of human behavior. Although philosophers have been interested in human thought for thousands of years, the field of cognitive science is relatively new, barely more than 100 years old. Given that the field is in its infancy, it is not surprising that there are more questions than answers. Indeed, one of the main discoveries of the field is just how difficult human cognition is to explain. Despite tremendous advances and discoveries over the past 100 years, the major problems remain unsolved. Indeed, outside of very constrained situations, it is very difficult to predict the cognitive properties and capabilities of any given individual or group of individuals.

To appreciate the complexity of human cognition, consider the task of a Warfighter listening to auditory information with an HMD (this example is modified from a discussion in Willingham (2007), see Chapter 2, *The Human-Machine Interface Challenge*, for a similar description of processes involved in perception):

> BASE: Where are you?
> WARFIGHTER: I have just reached the top of the hill.

The whole "conversation" lasts maybe a few seconds, and it might appear that this simple question and answer process is trivial. Indeed, people frequently do this type of activity without any trouble. In reality, though, the processes involved in even this simple behavior are exceptionally complex. Figure 15-1 schematizes some of the processes that must be involved as the Warfighter answers the question.

First, the Warfighter must recognize the sounds coming from the HMD as speech rather than other kinds of sounds. Speech interpretation is quite complicated. For example, studies of speech show that there are no clear pauses between spoken words in normal speech. Instead, the end of one word flows in to the beginning of a following word. Nevertheless, the Warfighter interprets the stream of sounds as corresponding to individual words in a sentence. Once the words are recognized, the solider has to interpret the meaning of the sentence. This too is a complex process that depends on the context in which the words are presented. In some contexts, the question might not be a literal request for location, but a statement indicating that the Warfighter is not where he or she should be (e.g., Where *are* you?). In still other contexts, the word *you* might refer to a group of soldiers rather than an individual.

Once the Warfighter knows what is really being asked, a decision has to be made whether to answer. If stealth is currently required, it may be better for the Warfighter to remain quiet. If an answer should be given, the Warfighter has to decide on an appropriate answer. The Warfighter has to know whether to reply in latitude and longitude coordinates or, as in this case, in reference to local geography. In other situations an appropriate answer might have been "Almost there," or "Two minutes away."

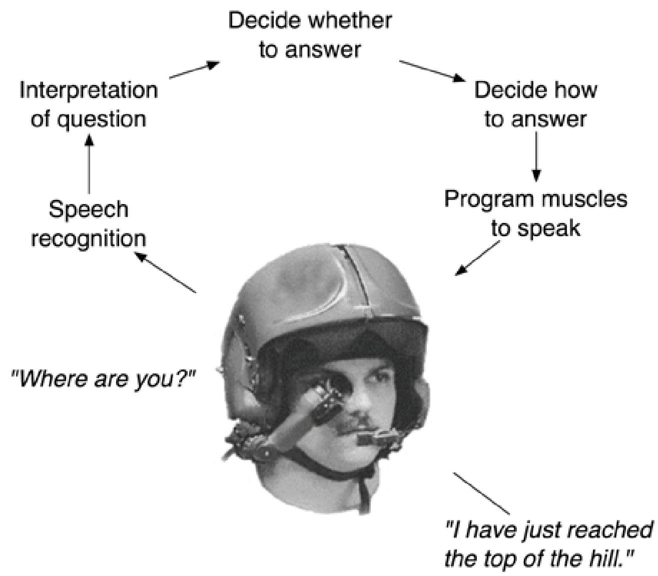


Figure 15-1. A few of the cognitive processes that may be involved in answering a simple question.

Once an appropriate answer is determined, the Warfighter has to send commands to muscles in the lips and tongue to form the speech sounds that are sent back to the base. These commands require exquisite timing to produce clear sounds.

Throughout the short conversation, the Warfighter is searching through memory for appropriate information. The soldier's memory contains all kinds of inappropriate information: details of the latest Spiderman movie, the taste of pancakes, and the name of his or her hometown. Somehow, all of this irrelevant information is not used, and instead the Warfighter selects the bits of information that are useful to the current situation.

As this brief example shows, even a simple conversation involves a complex set of processes. Cognitive scientists try to identify those processes and understand the details of each process. Each process itself can usually be broken down in to additional sub-processes that are also very complicated. Evidence for this complexity can be found in systems for artificial intelligence. There are still no computer algorithms that can interpret casual human speech, understand how to respond to simple questions, or generate speech that sounds quite like a human.

The problems in cognitive science are daunting, and even the best theories currently available are not going to give a complete description of how to analyze and design HMDs to take advantage of cognitive properties. However, such difficulties *do not* imply that studies of cognition have no advice to offer, as incomplete advice may still be better than no advice at all. There are two major contributions from cognitive science that can be applied to the design of HMDs.

The first contribution is the identification of different aspects of human cognition. University textbooks on cognitive science (e.g., Goldstein, 2005; Reed, 2004; Smith and Kosslyn, 2007; Willingham, 2007) generally organize and classify these aspects as: sensation and perception, attention, memory, knowledge, language, decision-making, and problem solving. All of these topics, and many specialized subtopics, are relevant to the use of HMDs, and they must be understood in order to optimize the usability of HMDs. If one can identify which aspect of cognition is influencing behavior, one can focus on designing the HMD to best match the known properties of that aspect. Much of this chapter is devoted to giving a brief introduction to these major topic areas and indicating how they might be related to HMD design and use.

The second major contribution from cognitive science is the development of empirical methods for studying cognition. The details of these methods are not trivial or obvious, as evidenced by their common misapplication.

Empirical reports of phenomena such as mind reading or extra-sensory perception can almost always be traced back to poor empirical measurements of human behavior and/or improper statistical control and analysis (e.g., Finegold and Flamm, 2006; Hinkle et al. 2003). Likewise, poor measurement of human cognition in the context of an HMD could lead to misunderstandings about how people will behave and interact with the system.

Many perceptual issues of HMDs have been explored in previous chapters. Here we try to focus on aspects of perception and cognition that have not already been discussed. Many researchers of cognitive science explicitly make a distinction between perception and cognition; although most researchers agree that the distinction is a fuzzy boundary with substantial overlap. Generally speaking, perception is about awareness of objects in the world, such as seeing a forest of trees fifty meters away or hearing a person walking through a forest. Cognition is about "higher-level" information processing, such as recognizing the particular forest as where you broke your arm when you fell from a tree two years ago. These processes are distinct in the sense that seeing a tree does not necessarily require committing knowledge of the tree to memory, using knowledge about the tree to guide decision-making, or attending to details of the tree's shape.

The following discussion highlights some important aspects of cognitive science as it relates to HMDs. In some cases, the discussion points out how important aspects of cognitive science have been used to better understand the design and use of HMDs. In other cases, the discussion explores where there appears to be an opportunity for future work. Many times, the cognitive relationships to HMDs are similar to the cognitive relationships for head-up displays (HUDs). Unless specifically mentioned otherwise, the following discussion generally applies to both HMDs and HUDs.

In this chapter, we will first describe methodological techniques for studying cognition, including experimental psychology, cognitive neuroscience, and computational modeling. We then discuss the general properties of cognition such as information processing and cognitive resources. Following this general overview, we explore specific subtopics of cognition, including perception, attention, memory, knowledge, decision-making, and problem solving. We then consider a variety of topics that have special interest for HMD design, including characterizations of human error, the effect of stressors on cognition, situation awareness, and workload. We then describe two case studies. One case study explores perceptual and cognitive issues of enhanced stereo-vision HMD designs. The other case study investigates visual phenomena related to a long-fielded aviation HMD, the Integrated Helmet and Display Sighting System (IHADSS). Finally, we discuss how properties of cognitive science can be applied to HMD design issues.

## Methodological Techniques for Studying Cognition and Perception

Cognitive science utilizes three main techniques to study cognition: experimental psychology, cognitive neuroscience, and computational modeling. A brief discussion of each of these techniques will help set the stage for understanding how cognitive effects can be studied with regard to HMDs.

### Experimental psychology

The field of experimental psychology uses scientific techniques and approaches to study behavior. The very idea of studying human behavior in a scientific way is relatively modern, dating to the 1800s (see Boring [1950] for a history of experimental psychology). Over the past 150 years, scientists have developed sophisticated techniques to isolate properties of human behavior. An important aspect of these techniques has been the development of statistical methods that analyze the experimental measurements. Most of our understanding of cognition comes from experimental studies of human behavior.

These empirical techniques reflect both the properties of the aspect of cognition that is being studied and the amount of control one has over an experiment. Most, if not all, cognitive processes are complicated and vary greatly across individuals and tasks. However, what varies and how it varies depends on what is being studied.

For example, studies of visual perception often use relatively few subjects and insist that data not be averaged across subjects. This emphasis reflects a general principle of visual perception that almost everyone behaves in roughly the same way to a carefully controlled stimulus. A key aspect of studies of perception is that a visual stimulus can be precisely defined and measured physically. This kind of control allows scientists to precisely measure differences between individual subjects. In many cases the differences are found to be quantitative rather than qualitative. That is, almost every subject behaves in a similar way (a more luminous stimulus appears brighter) but differ in the exact details (the absolute threshold for detecting a faint stimulus differs across subjects).

In contrast, studies of memory tend to use larger subject pools, and many memory phenomena are found only when data across many subjects are averaged together. This emphasis reflects the general principle that it is impossible to precisely control a memory "stimulus" because memory performance depends on many internal aspects of the subject, and these internal aspects may vary dramatically from one person to the next. Another difficulty in studying memory is that, unlike many studies of visual perception, one cannot repeat a stimulus and expect to get the same cognitive behavior. Thus, many effects can only be identified after averaging out individual differences from many observers.

Despite these (and many other) differences there are a number of empirical methods that are used in a variety of experimental studies. Table 15-1 (adapted from Smith and Kosslyn, 2007) summarizes some of the main experimental methods used in cognitive science.

Table 15-1.
Major behavioral methods used in cognitive science.

| Method | Example | Advantages | Limitations |
|---|---|---|---|
| Response time | Searching for a visual target that appears on an HMD. | Objective measure of behavior; indicates the time needed for cognitive processing. | Sensitive to uncontrolled details of the experimental context; speed-accuracy trade-off. |
| Accuracy (percent correct) | Memory recall, such as trying to remember a radio frequency. | Objective measure of behavior. | Ceiling effects (task too easy); floor effects (task too difficult); speed-accuracy trade-off. |
| Judgments | Rating workload on a seven-point scale. | Easy and inexpensive to collect; assesses subjective reactions. | Participant may not know how to use scale; may not able to report on processes of interest; may not be honest. |
| Protocol collection (speaking aloud one's thoughts) | Talking with a pilot about how to hover a helicopter. | Can reveal a sequence of processing steps. | Cannot be used for most cognitive processes, which occur unconsciously and in fractions of a second. |

Cognition inherently involves time. Although it may seem that people immediately respond to sensory inputs such as sounds and visual objects, scientific study demonstrates that such responses require time for information to be processed. One way of measuring temporal aspects of cognition is with a response time experiment.

In a response time experiment, a subject is given a task and asked to complete it as quickly as possible. A clock is started at the moment of task initiation and stopped at the moment of task completion. The time between the start and end of the task is the time needed for the subject to complete the task, i.e. the processing time. For example, a researcher may be interested in knowing how quickly a pilot can respond to a warning signal. By varying the properties of the signal, the context within which it appears, and other tasks the pilot might have to perform, one can gain insight into the cognitive mechanisms that are involved in processing the warning signal. Differences of even a few milliseconds can be important for identifying the underlying properties of cognition and in some situations can be operationally important. In general, a task that requires more cognitive processing will lead to longer response times.

One limitation of response time experiments involves the speed-accuracy trade-off. The speed accuracy trade-off refers to the general finding that errors go up when people have to respond more quickly. Giving people more time to process information generally leads to more accurate responses. This is important because it means that when comparing response times in two situations, you have to be certain that the accuracy is equivalent across the two situations.

Accuracy itself is a useful measure of behavior. Consider a memory task where a subject is shown a set of items and then later shown a test item. The subject's task is to judge whether the test item is one of the previously presented items or is a new item. The item in question could be either a visual or auditory object (e.g., a symbol or tone, respectively). A simple measure of human memory is to record the percentage of trials where the subject is correct on the task. A higher percentage indicates better memory. Such a measure can be recorded for a single subject across multiple trials of an experiment or for a single trial of an experiment across multiple subjects. Accuracy can likewise be used for any task where a correct/incorrect answer can be objectively identified.

A similar percentage statistic can also be used to measure behavior that does not have an objectively defined correct answer. For example, to measure the occurrence of visual afterimages (a percept of a visual pattern generated at the offset of a visual stimulus), a researcher would simply ask subjects to indicate whether or not they see an afterimage. There is no "correct" answer here; the subject must simply report what is seen.

Changes in percentage reports across varying conditions can be used to understand how mental mechanisms operate. For example, a researcher could measure percentage reports of afterimages with several different HMD systems. The researcher then could look for the HMD features that appear to be related to afterimage appearance and gain an understanding of what factors produce afterimages.

Two limitations of this kind of measurement are ceiling/floor effects and speed-accuracy trade offs. A ceiling effect occurs when performance is so good in all tested conditions that there is no evidence of any difference in cognitive processing. In a memory task where performance is 100% correct for all conditions, it is not possible to demonstrate that some items are more memorable than other items. This finding does not mean that there really is no difference, only that the task was so easy that the test does not demonstrate the differences. A floor effect is similar, but at the opposite extreme, where the task is so difficult that individuals are guessing.

The other measures in Table 15-1 are less objective than response time or accuracy. For judgments and protocol collection, the subject is asked to describe some aspect of their behavior or cognitive processes. These approaches are difficult to validate and depend on the subject knowing what to report. This is problematic because many aspects of cognitive processing are not consciously available (e.g., no one can describe how they remember the name of their home town, they simply "know" it).

The vast majority of investigations into cognitive factors of HMDs will use methods from experimental psychology. The techniques discussed above can be easily modified and adapted to a particular task or situation.

## Cognitive neuroscience

Cognitive neuroscience tries to relate human cognition to properties of the brain. The ability to identify such relationships has blossomed over the past twenty years with the development of brain scanning techniques such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and evoked response potentials (ERPs). These techniques can measure brain activity in space and time while a person is performing a specific cognitive task. Prior to such techniques, neuroscience studies were limited to observations of brain-damaged patients, single cell recordings during brain surgery, and animal studies. See Gazzaniga et al. (1998) for an introduction to this topic.

Brain processes operate on many different scales, so there are many different methodological techniques for studying the brain and relating it to cognition. Figure 15-2 reproduces a graph from Churchland and Sejnowski (1988) that shows how several different experimental techniques differ in terms of temporal and spatial resolution. Notice that significant processes in the brain operate over 11 magnitudes in duration and 8 magnitudes in distance. While new technologies have improved dramatically over recent decades, there is still no single technique that is capable of covering the full range of cognitive processes in the brain.

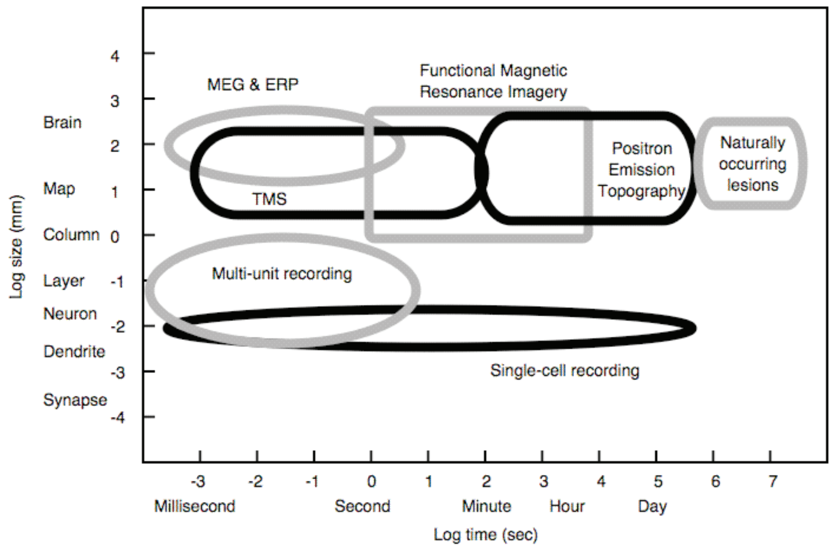


Figure 15-2. This plot shows the temporal and spatial scales of several different neuroscience techniques for studying cognitive neuroscience (adapted from Churchland and Sejnowski, 1988).

PET and FMRI track relative levels of blood flow and blood oxygen concentration (hemodynamics). PET traces a radioactive substance that is injected into the bloodstream. FMRI detects the properties of a radio wave in a strong magnetic field. The properties depend on the concentration of oxygen, which is related to blood concentration. For both of these techniques, higher blood flow to an area suggests that a brain region is involved in some cognitive task. The information from these brain scans is limited in spatial and temporal resolution. The techniques blur together responses from many thousands of individual neurons. (Neurons are a specialized type of cell that receive and send signals [messages] between the body and the brain and between different places in the brain.) Thus, one may know that a certain region of the brain is involved in a cognitive task, but be unable to identify which specific neurons in that region are involved. The same region of the brain (but different neurons) may also be involved in a quite different cognitive task. Temporal limitations are even more severe. Increases in blood flow occur in response to metabolic demands of neurons. However, changes in blood flow often lag neural responses. As a result, a sequence of mental events that occur faster than a few seconds (e.g., recalling an item from memory or responding to a warning signal) cannot be cleanly separated in the brain scan signals.

As an example where these imaging techniques have been used within the U.S. Army, a U.S. Army Medical Research and Materiel Command (USAMRMC)-sponsored PET study of complex cognitive task performance showed that during sleep deprivation there is decreased brain activity in several regions mediating higher cognitive functions and alertness; these include the prefrontal and posterior parietal cortices and thalamus (Thomas et al., 2000, 2003). Brain activity in specific subregions of the prefrontal cortex and thalamus, and an area of visual (occipital) cortex, were found to decrease across the 72 h sleep deprivation period and to correlate with the decreases in cognitive performance and slowing in saccadic velocity (Thomas et al., 2003).

Another well-known technique for measuring brain activity is the electroencephalogram (EEG), which tracks the electrical signals generated by neuron activity. These signals produce a pattern of activity across the scalp of a person. As a person engages in different cognitive tasks, the pattern of electrical activity changes across the scalp. This electrical activity also changes moment by moment during the processing of a cognitive task. This makes an EEG recording well suited to measure the temporal properties of brain events.

Unfortunately, the EEG signal is extremely noisy. The electrical signals must travel through various brain structures before reaching the scalp. To deal with the noise, researchers often average many EEG signals that are time-locked to the start of an environmental event (e.g., the appearance of a visual or auditory stimulus). The resulting averaged electrical signal is called an event related potential (ERP). The ERP signal has excellent temporal resolution and can have properties that appear to be related to certain cognitive events. On the other hand, it is often difficult to identify the spatial location of the signal that is read on the scalp. EEGs and ERPs generally have better temporal resolution than PET or FMRI, but poorer spatial resolution.

While the major techniques for measuring brain activity have been described, there are many others that are variations of these brain scanning techniques. It is not uncommon for researchers to combine several techniques to study a particular situation.

For the most part, cognitive neuroscience has yet to move beyond the research laboratories and directly influence the design or use of HMDs; this is not likely to change in the short term. The incorporation of the sciences of human factors and ergonomics into HMD design methods took more than a decade to come to fruition (some researchers would argue that the process is still continuing), and the progress of cognitive neuroscience will likely have to endure a similar progression. An understanding of which brain area is involved in a cognitive task is generally less important for HMD design than knowledge of the behavior itself. Long-term, theories and ideas from cognitive neuroscience will hopefully provide a more detailed understanding of the relationship between the brain and cognitive processing. With such knowledge, HMD design and use can be tailored to the properties of the brain. Future HMD designs may include feedback loops, where brain activity will be used to control the HMD's presentation content and duration via the neuroscience techniques described here, perhaps enhanced by other feedback signals such as oculomotor behavior.

## Computational modeling

A third investigative technique for cognitive science is the use of quantitative and computational models. There is general agreement that cognition is the result of the processing of information. The goal of this approach is to identify the details of the computational basis of various cognitive mechanisms.

There is no general model of human cognition. The nature and structure of existing models differ dramatically depending on the topic that is being modeled. For example, models of some aspects of visual perception (e.g., Itti, Koch, and Niebur, 1998; Raizada and Grossberg, 2003) draw strongly from both experimental data about human perception and neurophysiological data on the brain's visual system. These complex models are often defined by thousands of mathematical equations.

In contrast, some models describe behavior without direct regard for the underlying neurophysiological mechanisms. One of the most successful models in psychology describes the time needed to make a rapid hand movement to a target of a given size (S) at a given distance (D). Fitts (1954) proposed that the following equation models the movement time (MT):

$$MT = a + b\log_2\left(\frac{2S}{D}\right). \qquad \text{Equation 15-1}$$

The terms *a* and *b* are free parameters that vary for different tasks. The term $log_2$ refers to the logarithm, base 2. While this equation ignores the vast complexity of the brain and cognitive processing, it nicely captures properties of human behavior and can be used to guide the design of systems for human-computer interaction (e.g., Guiarda and Beaudouin-Lafon, 2004; Francis and Oxtoby, 2006).

Still other types of models draw on ideas from computer science and artificial intelligence. For example, a cognitive architecture called Adaptive Control of Thought—Rational (ACT-R) is a system that describes how information is stored in memory and later retrieved from memory (Anderson, 1993). ACT-R tries to identify and model the procedures involved in how the brain is organized to produce cognition. Another model that combines ideas from artificial intelligence and psychology is the Executive-Process/Interactive Control (EPIC) model for human information processing (Kieras and Meyer, 1997). This cognitive architecture model tries to account for the detailed timing of human perceptual, cognitive, and motor activity. EPIC provides a framework for constructing models of human-system interaction. The model generates events (e.g., eye movements, key strokes, vocal utterances) whose timing is accurately predictive of human performance. For both of these models, a special-purpose version must be created for any given situation. A model created to explain details of reading would not be applicable to a model created for responding to warning sounds.

In principle, computational theories and models have great promise for contributing to the design and use of HMDs. A computational model that can accurately predict human behavior can reduce one of the biggest burdens on HMD design by substituting a computer model for a human subject during development. Indeed, there have been several efforts to use computational theories and models to guide computer interface design (e.g., Byrne et al., 2004; Card et al., 1983; Foyle et al. 2005; Kieras and Meyer, 1997; Liu et al., 2002). Many of these efforts have been successful in matching human data, although the models are usually not complex enough to apply outside of very limited domains. An excellent review of the successes and difficulties of applying theoretical ideas to human-computer interface design can be found in Rogers (2004).

In practice, it takes a substantial amount of work to identify what aspects of a situation need to be included in a model. In addition, one often discovers that a model cannot deal with some important details (e.g., a model of visual perception may have no stage for decision-making). There is often a difficult conundrum related to model complexity. Simple models fail to match empirical data or provide predictions of human behavior because they lack the sophistication and fluidity of human cognition. On the other hand, more complex models become mired down in issues of parameter settings. As the models become more complex, many different parts of the model contribute to many different behaviors. As a result, it becomes increasingly difficult to identify the relative contribution of any part of the model. Teasing apart the different model contributions requires an enormous amount of empirical work.

Much of the difficulty in computational modeling revolves around the fact that there is no generally agreed upon theoretical framework for how cognition operates. There is agreement that cognition involves the processing of information, but this leaves unspecified the details of how information is represented and the precise handling of the information. Without a general framework, the field of cognitive science has developed a variety of models that each deal with some particular aspect of cognition, but these models are often incompatible. For example, models of visual perception (e.g., Itti and Koch, 2001; Raizada and Grossberg, 2003) and of working memory (e.g., Baddeley, 2003) are so different that there does not appear to be a way to connect one to the other.

## Cognitive Resources

The previous section suggests that experimental approaches provide the most information about cognitive processing, and that the neuroscience and computational techniques do not yet offer much additional insight to HMD design issues. While there is some truth to this suggestion, all three techniques do agree on a very important characteristic of cognition that is extremely important for HMD design- the concept of limited cognitive resources.

Cognitive resources refer to information-processing capabilities and knowledge that can be used to perform mental tasks. Different cognitive tasks seem to involve different information processing systems, and the resources and limits of these systems determine the cognitive capability to perform a given set of tasks. One of the main goals of cognitive science is to identify the properties of these systems and characterize their limits. This is true of experimental, cognitive neuroscience, and modeling approaches.

A number of cognitive science theories suggest that individuals have a limited processing capacity (e.g., Broadbent 1958; Kahneman, 1973; Lebiere et al, 2002; Posner, 1978; Wickens, 1984). The phrase *cognitive capacity* is often interchangeable with that of *cognitive resources* (Harris and Muir, 2006). Wickens (1992) disagrees with this, defining *capacity* as the maximum or upper limit of processing capability, while *resources* represent the mental effort supplied to improve processing efficiency.

One example of such a limitation can be seen in the resolution of the human eye. The best visual resolution of the eye is in a small area (approximately 1.5 millimeters diameter) of the retina known as the fovea. Visual discrimination tasks that require fine spatial detail (such as reading of small text) can only be accomplished with images that fall onto the fovea. As a result, individuals move their eyes in order to take in different parts of a scene with sufficient detail to complete the task.

A second example of processing limitations is revealed in reading, where only one thing can be read at a time. Consider the two sentences in Figure 15-3. If you focus on the x's in the middle and go from top to bottom, you can read either the sentence on the left or on the right. However, it is not possible to read both sentences at the same time. There is a fundamental limitation in the cognitive processes involved in reading that prevent dual reading.

| | | |
|---|---|---|
| You | x | Is |
| can | x | it |
| read | x | time |
| this | x | for |
| text | x | a |
| without | x | quick |
| any | x | snack |
| trouble. | x | yet? |

Figure 15-3. The letters are large enough that you can read any individual word while looking at the central x. However, you cannot read the left and right sentences simultaneously (adapted from Wolfe et al., 2006).

There are similar limitations for other aspects of cognition. In a visual (or auditory) scene with several stimuli, a person can only attend to a relatively small number of stimuli simultaneously. There is some variability in estimates of the exact number, but it appears to be on the order of 1 to 4 (Cowan, 2001; Davis, 2004).

Likewise, human memory seems to be divided into several subsystems with each having its own processing limits. Long term memory (LTM) seems to have almost unlimited capacity to store new information, while short term memory (STM), or working memory, has a much smaller capacity to hold information, limited to 4 to 7 items (see Neath and Surprenant (2003) for an introduction to the properties of human memory). This limitation is easily demonstrated using Figure 15-4. Get a pencil or pen and cover the figure with a piece of paper so that the letter strings cannot be seen. Slide the paper down so that the first row can be seen. Study the letters for a few seconds, and then cover the letters with the paper. Now write down the letters in the row in exactly the same order they were given. Repeat this task for each of the next rows. Finally, check your memory performance. Most people have no trouble recalling all the items in the first few rows, but start to have difficulty recalling a list of items longer than 7 items. This limitation reflects the properties of a STM system that can only process a limited amount of information. When the list of items exceeds that system's limit, some information is forgotten.

SDK
TJPK
WZCML
CNBSKW
YLKDRWP
QSCVNTKF
BNCJWFHSL
XNBMJSGFHDK
RTDKSLCNMNBP

Figure 15-4. A demonstration of resource limitations for short term memory. See the text for details.

These cognitive limits have important consequences for the design and use of an HMD and related systems. The processing limits of human cognition emphasize that having information physically available to a person is not the same thing as ensuring that the person processes (or can process) the information. A system that presents too much information (visual, auditory, or both) may be worse than a system that leaves some information unavailable because the former overtaxes the processing capabilities of various cognitive systems.

One important aspect of cognitive processing involves assigning cognitive resources to different tasks. As described below, certain cognitive systems are involved in a variety of different tasks, and often the processing limits of those systems restrict how many tasks can be accomplished. Just as important as the processing limits is the need and ability to switch between different tasks. For example, McCann et al. (1993) found that it took effort and time to switch from processing information on a head-up display to processing information in the world.

Some cognitive behaviors seem to require very little effort. When a task is highly practiced it sometimes becomes *autonomized* and appears to require very little cognitive resources (Logan, 1988). A common example of automaticity is driving a car. A novice driver must expend a significant amount of cognitive resources to insure that many different factors are properly maintained (e.g., speed, distance from other cars, staying in the appropriate lane). With extensive practice, these monitoring activities become autonomized and happen so automatically that people are not even aware that such monitoring is occurring.

One the one hand, it is very beneficial to have certain behavior become autonomized because such behaviors are performed effortlessly and reliably. On the other hand, without conscious monitoring of behavior, autonomized behavior may be insensitive to small deviations from normal conditions and lead to inappropriate responses (Endsley, 1999).

## Cognitive Functions

The previous sections of this chapter introduced some important concepts in cognitive science and mentioned some of the methods, approaches, and issues in the field. We now turn to a discussion of some of the major topic areas in cognitive science and discuss their relationship to HMDs. These topics include perception, attention, memory, knowledge, decision-making, and problem solving. Some topic areas are more important than others, and there are clear imbalances in the amount of research related to the different topic areas. Indeed, for some topics, such as visual attention, there are so many studies that it is not practical to review even a small minority of interesting findings. In contrast, for other topics there appears to be virtually no research activity.

## Perception

Perception is conscious sensory experience. It is a combination of a stimulus signal producing transduction to neural receptors and cognitive mechanisms interpreting those signals. Perception deals with psychological awareness of objects in the world based on the effect of those objects on sensory systems. An integrated HMD must satisfy the user's need for visual and auditory perception. Cutting-edge systems also are incorporating haptic (touch) systems to transmit information.

### Visual perception

The most basic requirement of an HMD with regard to visual perception is that the HMD needs to be able to generate light patterns that can be detected by the earliest stages of the visual system (i.e., the eye). The necessary intensity, contrast, field-of-view, spatial frequency, temporal responses, and spatial resolution for an HMD to generate appropriate stimuli for visual perception are fairly well understood. This is an important topic that has been dealt with in other chapters (2, 4, 6, 7, 10, 12, 14, 16) in this book, in previous edited books (see especially Chapters 5 and 6 in Rash [2000]), and in several reviews (Crawford and Neal, 2006; Edgar, 2007; Patterson et al., 2006). Rather than repeat this discussion, it will be fruitful to look at other aspects of perceptual experience beyond the visibility of stimuli.

Ultimately the perception of visual stimuli is an awareness of objects in the world rather than knowledge about patterns of light. Perception is *not* a copy of the retinal image. This is easily demonstrated by looking at Figure 15-5. Unless you have previously seen this image, it is quite challenging to identify how the different elements of the image group together to produce a coherent picture of an animal. Indeed, most viewers are unable to identify the object the first time they see this image.

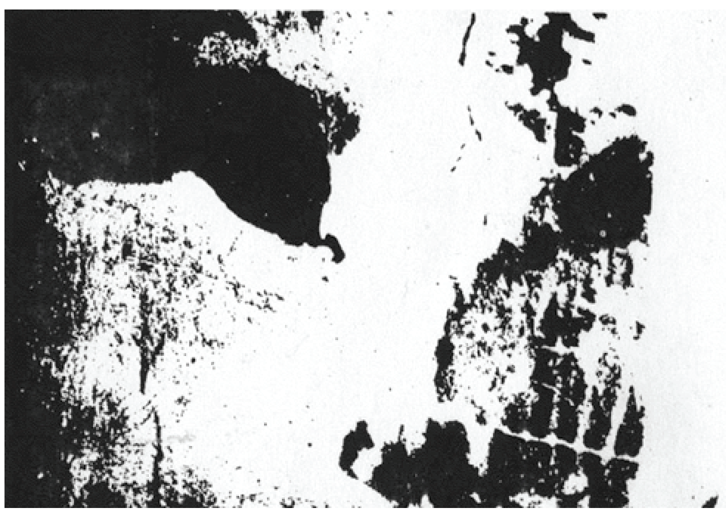

Figure 15-5. What shape do you see in this figure? If you cannot identify an animal after a few minutes, look at Figure 15-6 for clues about the shape.

An outline to help you identify the animal is given in Figure 15-6. After viewing that figure, return to Figure 15-5. It should now be fairly easy to see the object in the image. Your memory of how to organize the image elements influences your perceptual experience. In fact, you will probably never be able to see the image as it appeared the first time you saw it. Instead your memory will forever bias it to look like the object identified in Figure 15-6. Note that the retinal image has not changed at all from one viewing to the next.

One reason Figure 15-5 is difficult to interpret is because it is not clear how the black and white patterns group together. Grouping of image elements is a basic problem for visual perception. Due to occlusion from other objects, shadows from retinal veins, and noise in the physiological pathways, different parts of an object are often spatially disconnected. The visual system deals with this problem by grouping together separate parts of a visual scene to produce a coherent representation of groups of elements. This type of perceptual organization is critically important for understanding a visual scene. In many instances the process is so automatic and reliable that people do not realize that different parts of an image are being grouped together by the perceptual system.

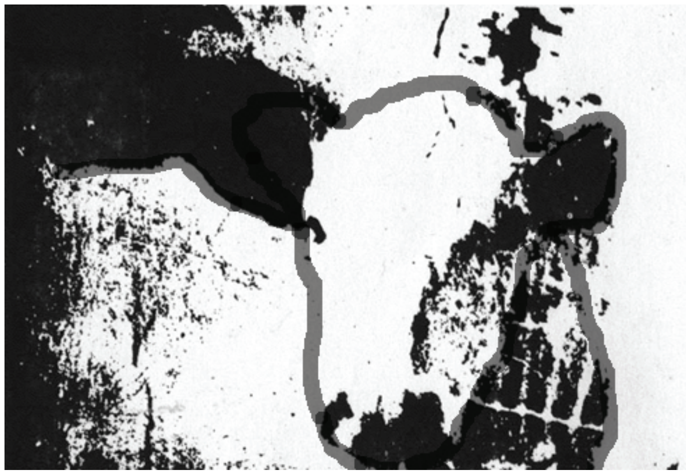

Figure 15-6. The gray lines outline the shape of a cow. Now looking at Figure 15-5 should cause you to see the cow shape.

For example, Figure 15-7a shows what appears to be a dark ink stain in front of variously oriented capital letter Bs (Bregman, 1981). Each letter B consists of multiple parts that are separated by the ink stain. The visual system is somehow able to link together the disparate parts of individual Bs to produce a coherent and meaningful perceptual experience. The presence of the ink stain appears to be an important part of this grouping process, because when it is absent, as in Figure 15-7b, the elements do not group together to from letter Bs. Even though the amount and pattern of light corresponding to the B's is the same in both images, the differences in grouping change the perceived objects in the scene.

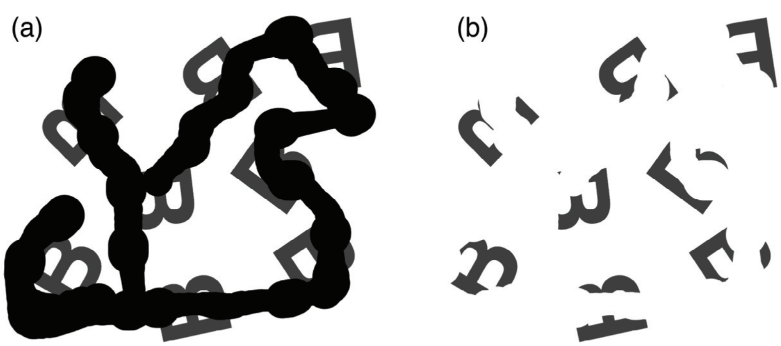


Figure 15-7. The rotated letter B's are visible in (a) when occluded by dark ink. In (b) the dark ink is replaced by the background color, which makes the B's more difficult to recognize.

Figure 15-8 shows other examples of perceptual grouping (Kanizsa, 1979; Wertheimer, 1923). In Figure 15-8a, the dots can appear to form vertical columns or horizontal rows (left) depending on the spatial proximity of the dots or their color similarity. In Figure 15-8b, there is a grouping among the slices of the Pac-Man cutouts that produces an illusory white triangle that appears to float above the other elements.

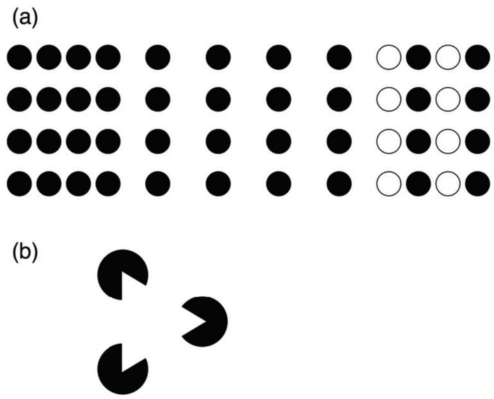


Figure 15-8. The dots in (a) can be perceived to group in to horizontal rows (left) or as vertical columns (middle and right), depending on the proximity of the dots and their colors. In (b) an illusory triangle is perceived in front of the discs.

Grouping effects such as these are very important for HMD displays. Many displays have sparse and disconnected elements that must be grouped together to form a coherent percept. Generally speaking, designers can quickly recognize when things do not group together properly because nearly every one's grouping process operates in a similar way. Still, there is the potential for inappropriate grouping if display systems are altered or used in ways that were not anticipated. Symbols that group together well under one condition, may not group together in a similar way under other conditions.

There are several computational theories of perceptual organization. Perhaps the most sophisticated theory is the neural network model proposed by Grossberg (1997). In this model the visual scene is analyzed by parallel processing streams that process boundary information (edges) and surface information (colors, brightness) in a complimentary way to identify objects in depth. A key part of this analysis involves grouping together edges in an appropriate way. However, even this theory is unable to take an arbitrary complex scene and predict how elements will be grouped. This is because the process of perceptual organization (and the model) is very sensitive to many details of the scene. A small change of color, contrast, or position can lead to a radical reorganization of the grouping of elements.

## Auditory perception

In addition to visual information, many HMDs provide users with auditory information. Analogous to the presentation of visual stimuli, a basic requirement of an HMD is for the device to reliably present auditory stimuli that can be detected by the earliest stages of the auditory system (outer and inner ear). Appropriate intensities, frequencies, and durations of sounds are discussed in other chapters in this book (5, 8, 9, 11, 13, 14) and chapter 8 in Rash (2000). Rather than repeat this discussion, it will be fruitful to look at other aspects of perceptual experience beyond the detectability of stimuli.

Ultimately the perception of auditory stimuli is an awareness of sound sources in the world rather than knowledge about patterns of air pressure. A variety of auditory cues are used to derive an understanding of the location and properties of various sources in an environment. This kind of auditory scene analysis allows individuals to segregate different auditory streams. As for visual perception, these processes are often automatic and are so reliable that people do not realize that there are specific cues involved in tracking and sorting auditory streams.

For example, localizing a sound in three dimensions involves several different cues. Azimuth (horizontal location) is largely based on interaural differences, where a property of sound is different across the two ears. One such cue is an interaural time difference. A sound on your left side will reach your left ear before it reaches the right ear. Similarly, a sound on your left side will have a higher intensity in your left ear than in your right ear because the head casts an acoustic shadow that leads to an interaural level difference. Identification of a sound source's elevation is largely based on frequency cues. The head and ear decrease the intensity of some sound frequencies and increase others. These effects depend on the shape of the head and ear between the inner ear and the sound source. Sounds in different locations are influenced by different parts of the head and ear folds, and these differences change the content of the sound in a way that reveals the sound's location. Further details can be found in textbooks on perception (e.g., Goldstein, 2002; Wolfe et al., 2006) and in other chapters in this book. Many HMDs include ear coverings that interfere with normal auditory perception and only allow for verbal communication. Systems that include 3D audio earphones reintroduce many of the auditory cues described above. 3D audio systems can also be used to introduce entirely new kinds of information, so simulated sound sources at different perceived locations can provide multiple types of information. Despite substantial technological developments and enthusiasm for the idea, 3D audio systems have had limited impact in aviation cockpits (Johnson and Dell, 2003).

Auditory perception differs in many ways from visual perception. In some respects they provide complimentary information about a complex environment. For example, visual perception can provide information about objects that are too far away to be heard, while auditory cues can provide information about objects that are hidden from view. Several cockpits use these differences to insure information processing in various scenarios. For example, Martin et al. (2000) discuss how 3D audio displays operate normally even with hypoxia (introduced at a simulated high altitude). Such audio displays can thus continue to provide sound localization in situations where visual cues may start to fail. Given the differences between the two systems, it is not surprising to learn that other aspects of cognition (attention, memory, and knowledge) treat auditory and visual information differently. Some of these differences are discussed below.

### Tactile perception

A third source of perceptual information in some HMDs comes from tactile interfaces that send information through the sense of touch. Chapter 18 (*Exploring the Tactile Modality for HMDs*) discusses the physiological basis of tactile perception in depth, and describes how vibrotactile interfaces might be applied to HMDs.

The primary motivation to explore the use of tactile perception is to provide a means of avoiding processing limitations imposed by the visual and auditory modalities. As discussed above, there are limits on how much information can be processed by any cognitive system. The hope is that the tactile system will complement the visual and auditory systems and provide an independent source for additional information. Such a source is not likely, however, to overcome processing limitations of higher-level (non-perceptual) cognitive systems.

One of the challenges faced by HMD designers exploring tactile perception is to identify what kinds of information can be conveyed through the tactile perceptual system. By the nature of its physiology, touch is closely tied to other perceptual experiences such as pain, temperature, and pressure. Likewise, individuals rarely use touch as a static detector but instead make specific movements to explore properties of their environment (Lederman and Klatzky, 1987). For example, lateral motion across a surface is used to reveal the texture of a surface, while static contact is used to reveal the temperature of an object.

## Attention

Because all cognitive systems have limited processing capability, there is a distinction between the full spectrum of environmental stimuli and the amount of information that is actually processed. The mental processes that are involved in producing (or resulting from) this distinction are referred to as attention. The very same physical stimulus can be processed very differently when attended compared to when unattended. If someone asks you a question while you are busily thinking about something else, you may not even hear the question. The person may have to nudge you to draw your attention.

In casual conversation, people tend to use the term attention to refer to a voluntary focusing of attention. There is a feeling that one can direct attention to different aspects of the environment. In reality, attention is not based on a unitary mechanism, but involves the properties of many different cognitive systems.

Cognitive scientists make a distinction between voluntary (top-down) and involuntary (bottom-up) attention (Pashler, 1997; Posner, 1980). Voluntary attention occurs when a person makes a noticeable cognitive effort to remain focused on a particular task. Involuntary attention is often related to some environmental stimuli (such as loud sounds or flashing lights) that seem to automatically draw a person's attention.

Attention effects can occur for many cognitive processes. If someone reads a phone number to you, you may need to mentally rehearse it in order to remember it for a short period of time. If someone interrupts you to ask a question, the memory resources that you would have exerted on rehearsing the phone number are now allocated to the conversation. As a result of this reallocation, the phone number may be forgotten. When making decisions or solving problems, individuals often attend to some kinds of information more than to other kinds of information. The attended information plays a larger role in the characteristics of the decision or the arrived-at solution.

Thus, attention is a multi-faceted term that applies to many different aspects of cognitive processing. This idea is part of many views of cognition, and it plays a central role in Wickens' (1980, 1992) model of human information processing. In the model there are limited amounts of attentional resources that must be distributed effectively to complete a given task.

Attention effects can have large (and startling) impacts on behavior, and they are present at many stages of cognition. As a result, attentional effects are the most commonly studied aspect of cognition in relation to HMDs. Ideally Wickens' theory would identify how to work within the limited capabilities of each cognitive system and would predict bottlenecks in the flow of information from one system to the next. Indeed, the theory has been used for just this purpose (Wickens et al., 2005). However, the allocation of attentional resources cannot be directly measured, so it is often difficult to judge which cognitive system is ultimately limiting performance on a task.

It is not practical to consider all possible ways attention can interact with an HMD; however, this section will discuss three topics related to attention effects with HMDs: attentional allocation and information redundancy, visual search, and change blindness and cognitive tunneling. These particular topics were chosen because they apply to many different situations and highlight notable relationships between attention and HMDs.

### Attention allocation and information redundancy

One of the earliest decisions that must be made in the design of a display system is what modality to present a specific piece of information. Visual images and sound are the two most commonly used modalities, but it is not always clear which is best for a given situation.

Wickens' multiple resource model (Wickens, 1980, 1992) suggests that the best modality depends on how the modalities are being used for other tasks. If the visual system is busy with many other tasks, then a visually presented stimulus may overtax the resources of the visual system and thereby lead to errors or poor performance. In such a situation, it may be better to convert some of the processing load to the auditory domain. The more general goal is to avoid resource competition, where multiple stimuli and tasks effectively compete for cognitive resources. By distributing the stimuli and tasks across separate systems, resource competition can be reduced.

On the other hand, stimuli in some modalities have bottom-up attention properties that preempt other cognitive systems. For example, an auditory stimulus seems to interfere with the processing of visual stimuli more than the other way around (Helleberg and Wickens, 2003). This is perhaps because an auditory stimulus is necessarily transient and must be acted on before being forgotten. Such preemptive effects can introduce difficulties in completing other tasks. In contrast, a static visual presentation of a stimulus will remain visible for a longer period of time. An individual can complete a current task and then investigate the visual stimulus when it will not interfere with other tasks.

Helleberg and Wickens (2003) explored modality effects for the presentation of simulated data link air traffic control (ATC) instructions. The instructions were presented either visually, auditorially, or both, while subjects flew simulated cross-country flights. The subjects in this study did not use an HMD, but the issues are relevant for both situations. At various times in the flight, ATC instructions would appear and subjects had to perform a task using the instructions.

The influence of processing the ATC instruction was measured by tracking errors in a prescribed flight path. Larger errors indicated greater difficulty in dealing with the ATC instructions. Helleberg and Wickens (2003) expected that performance would be best when the instructions were redundantly presented with both visual and auditory modalities. The auditory stimulus would be processed by a separate cognitive system from the systems involved in maintaining the flight path (largely a visual task). At the same time, the permanence of the redundant visual presentation would allow subjects to continue with a given visual task and then transfer their cognitive resources to the ATC instructions at the first available opportunity.

The empirical measures did not match the expected pattern. The best performance was for the visual presentation of the ATC instructions. The worst performance was for the auditory presentation of instructions. The performance for the redundant modality presentation was in between the other two.

This conclusion is notable because it demonstrates a common pattern in this kind of research. First, it is very difficult to use a model to predict what will happen in any particular situation. There are almost always multiple effects that work in opposite directions, and which one dominates a particular conclusion is sensitive to a great many factors. Second, the conclusion is almost always limited to the details of the experiment. The conclusions from this study are valid for the particular ATC instruction set, the flight paths, and the simulated aircraft. If any of those variables changed, the conclusion may be altered. One can easily imagine scenarios where the auditory presentation would lead to better performance than the visual presentation of ATC instructions. Moreover, as Helleberg and Wickens (2003) noted in their conclusion section, with appropriate training their subjects might have been able to learn to utilize the redundant display in a more efficient way.

### Visual search

An HMD usually provides more than one piece of information at a time. A user who interacts with the visual presentation on an HMD must often search the display to identify a specific item that is relevant for a current task. This type of search is ubiquitous throughout daily experience, and there have been thousands of empirical studies that investigated the details of how such a search is performed. There are many varieties of visual search experiments, but most require the subject to observe a scene and either report when they have found a target item or to decide that the target item is not present. Measures of human performance generally include percentage correct and reaction time.

Cognitive scientists use the visual search paradigm to gain an understanding of the mechanisms and principles of cognitive systems (e.g., Treisman and Gelade, 1980; Wolfe, 1994). Both bottom-up and top-down attentional components play an important role in visual search tasks. Different display designs can alter the bottom-up attentional effects of different targets. A well-designed display will lead to bottom-up attentional effects that guide the user's attention to needed information. Likewise, top-down knowledge of the target properties can modulate the bottom-up information effects (Itti and Koch, 2001; Wolfe, Cave and Franzel, 1989).

Visual search is such a basic part of many tasks that it is often used to judge the quality of various display systems. For example, Hollands et al. (2002) used a visual search task to compare cathode ray tube (CRT) and liquid crystal display (LCD) monitors for possible use in military aircraft. They concluded that the degradation of LCD pixels with off-axis viewing made them unsuitable for some situations. (Note: Off-axis luminance and contrast in LCD monitors has greatly improved since this study.)

A potential problem for HMDs is that so much information can be placed on the visual display that it becomes difficult to find needed information. Studies of visual search suggest that the solution is to make an item-of-interest very distinct from other items (Wolfe, 1998). This solution is the basis for keeping some visual and auditory properties reserved exclusively for warnings (Smith and Mosier, 1986) or to use redundant multi-modal alarms (Nelson and Bolia, 2005). A distinct item-of-interest can be quickly found regardless of how many other items are on the display. In contrast, an item-of-interest that shares features with other items on the display may be difficult to detect and become increasingly difficult to find as more other items are present. However, in real world use of an HMD, what is labeled as an item-of-interest in one context may be clutter in a different context and vice-versa. Thus, it is difficult to make all items sufficiently distinct from other items.

Yeh and Wickens (1998) investigated a cueing approach to the clutter problem, where potential target items were cued with an arrow drawn on the HMD. Cueing led to faster reaction times and higher accuracy than if cuing was not used. Such cueing did come with a cost, however. The subjects were also asked to complete a secondary task (jamming enemy radio signals when necessary); accuracy at this secondary task was poorer when the targets were cued on the display. Presumably, the attentional pull of the cue hindered resource allocation to the secondary task. Similar results also were found for a hand-held display with similar information.

Other attempts to improve visual search include decluttering techniques (e.g., Schultz et al., 1985). With decluttering, items that are deemed to be irrelevant to the current task (e.g., commercial aircraft that are far away) are given reduced visibility or removed from the display. For this approach to be successful, one must be able to identify an algorithm for selecting irrelevant items in a way that fits the user's intuitions and expectations. St. John et al. (2005) used a decluttering heuristic for the display of a simulated naval air defense task. They found that response times to important events on the display were faster for decluttered displays than for a no-declutter display.

A common limitation of these (and many other studies) is that it is uncertain how well the results generalize to other situations. The decluttering algorithm used by St. John et al. (2005) was specially crafted for the display and task. Some displays and tasks may be more difficult to declutter. Likewise, the benefits of cueing surely depend on the task and details of the items that are being searched as well as the abilities and cognitive style of the operator.

Perhaps the most important lesson from studies of visual search is that there are multiple effects of adding information to a display. In addition to giving the user more information, the added information includes a potential cost for the user trying to find items-of-interest on the display. This conclusion echoes the experiences of HMD designers. As Newman and Greeley (1997) noted, "…there is an absolute need to keep the amount of information to the minimum necessary for the task. The reason is simple; the reason for a see-through display is to see through it."

### Change blindness and cognitive tunneling

Attentional effects can be so strong that subjects will report not seeing otherwise very salient stimuli when the subjects are engaged in a demanding task (Simon and Levin, 1997). Large changes in a visual scene that co-occur with other elements appearing or disappearing, eye blinks, or movie cuts can be unnoticed even when subjects know to look for some change (Rensink et al., 1997). This effect is known as change blindness. A version of this effect can be seen in Figure 15-9, where two similar images are shown. There is a significant difference between the two images, but it is rather difficult to locate and identify the difference.[1]

Similar difficulties can be found for many situations that are relevant to environments that use HMDs. In general, individuals are not very good at noticing changes in a scene unless they are attending the object that changes. Other changes in a scene (such as gun flashes) can misdirect attention from a scene and lead to a failure to detect a significant change. Should such effects occur on an HMD during critical phases of a maneuver, the results could be devastating.

On the other hand, Triesch et al. (2003) used an HMD to set up a virtual reality situation where subjects moved (virtual) tall or small bricks to conveyer belts. On ten percent of the movements, the bricks changed height. The height change was scheduled to co-occur with an eye saccade. Subjects usually did not notice the change when the task simply involved placing the bricks on the belts regardless of brick height. As the task changed to make brick height more significant, subjects were more likely to report noticing the change in brick height. This finding suggests that the impact of change blindness is modulated by the task being performed by the subject.

Cognitive tunneling refers to a difficulty in dividing attention between two superimposed fields of information (e.g., HMD symbology as one field and see-through images as another field). It is also sometimes called attentional tunneling or cognitive capture. Some of these effects are similar to effects categorized as change blindness. In the aviation environment, such effects can lead to serious problems. Fischer et al. (1980) and Wickens and Long (1995) found that pilots sometimes did not detect an airplane on a runway when landing while using a HUD system. Clearly, the importance of the detection task is not enough, by itself, to overcome some change blindness effects. Cognitive tunneling is an extreme form of a trade-off between attending to displays and attending to the outside world. Brickner (1989) and Foyle et al. (1991) noted that a HUD improved monitoring of altitude information in a simulated flight, but at the expense of maintaining flight path. Shelden et al. (1997) suggested that cognitive tunneling can be avoided by having HUD symbology be linked to the outside world. The meta-analysis on cognitive tunneling by Fadden et al. (1998) is a good starting point for further exploration.

## Memory

Human memory interacts with attention and perception effects. Indeed, many failures of attention are described as breakdowns in memory for recent events. Cognitive scientists have identified many components of memory (Neath and Surprenant, 2003). Figure 15-10 describes some of the different types of memory and their properties. One major distinction between memory systems is between short term memory (STM) and long term memory (LTM). As its name implies, short term memory deals with memory of items for relatively short periods of time (a few seconds). Generally, STM has a relatively small capacity, meaning that it can hold only a few items before some forgetting takes place. A more elaborated view of this system sometimes goes by the term *working memory* (Baddeley, 1986, 2003), which has been broken down in to a variety of subsystems that process information in a variety of ways. Different subsystems are hypothesized to deal with different types of information.

The visuospatial sketchpad is hypothesized to deal with visual short term memory (VSTM). VSTM would play an important role in, for example, monitoring a variety of potential threats on a display. Duncan et al. (1997) found that judgments of target features were faster when the features were on a common object rather than on different objects. On this basis, they suggested that only one item can be attended and held in VSTM at any moment in time. In contrast, Trick and Pylyshyn (1993) noted that subjects could reliably track three or four moving targets among a field of non-targets. This result (and others) suggests that VSTM can hold around four objects (Cowan, 2001). However, there is some debate (e.g., Davis, 2004) about the validity of these conclusions and their meaning.

[1] Look at the engine on the wing.

Figure 15-9. These two similar images have a significant difference that is surprisingly difficult to find.

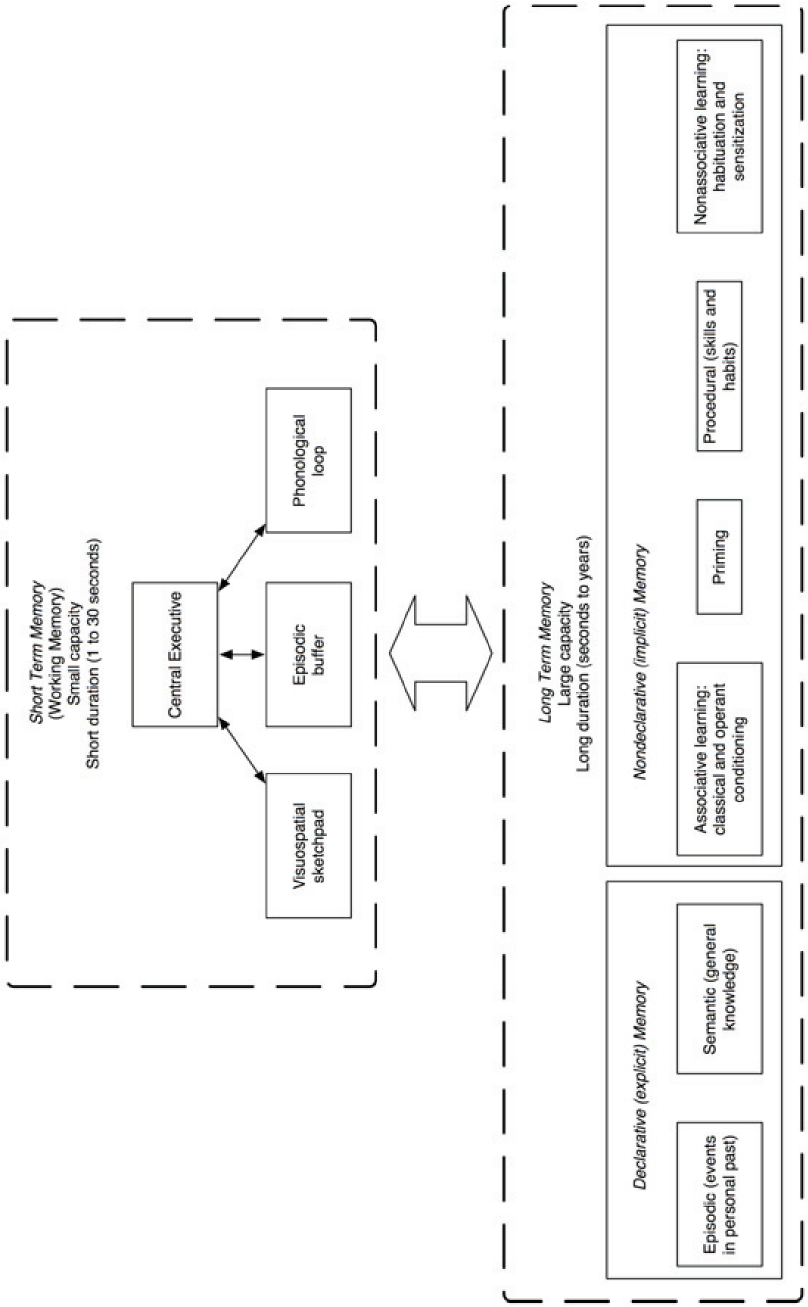


Figure 15-10. Some hypothesized memory systems.

The phonological loop is hypothesized to deal with speech and language information in working memory. Any spoken or read information that needs to be remembered for a short period of time would be held in the phonological loop. The content in the phonological loop appears to be speech sounds. This can include both spoken words and visual words that are read and then converted to speech sounds in the phonological loop. The phonological loop includes a subsystem that stores sound information for a few seconds and a system that mentally rehearses items in the loop. Forgetting often occurs because items are not rehearsed.

The working memory theory is not intended as simply a description of memory, but as a system for manipulation of information in complex tasks that involve memory. One implication of the properties of working memory is that tasks will be easier to perform if information processing can be distributed across the different components of working memory (e.g., visual and spoken information is involved) rather than weighted exclusively on one component. Wickens (1980, 1992) has made a similar observation with his multiple-resources model.

Working memory interacts with long term memory (LTM). LTM holds some information for very long periods of time (essentially a lifetime) and has a very large capacity that does not seem to be exhausted with an average human lifespan. Studies of memory suggest that LTM can be broken down in to a variety of subsystems. One major split is between declarative (explicit) and nondeclarative (implicit) memory. Declarative memory refers to memory experiences that can be explicitly recollected or declared. This includes episodic memory of particular events in your life and semantic memory, which refers to general knowledge. When you recollect what you had for breakfast this morning, you are probably recalling the memory from episodic memory. You recall the information and part of the memory involves the context in which the event occurred. On the other hand, when you recall your mother's name, you probably recall the information from semantic memory. Here you recall the memory, but it (probably) does not include knowledge about the context in which you learned that information.

Nondeclarative memory refers to nonconscious forms of LTM that influence behavior but are not explicitly recalled. This includes knowledge that is implied rather than directly known. For example, a practiced driver knows how to hold the steering wheel to appropriately direct a car, but the driver may not be able to explain to someone else how to perform this behavior. Nondeclarative memory is often a "feeling" of knowledge.

HMD devices may alter how people remember information. In a certain sense, the HMD can become another source of memory that can be tapped to get information about past events. Hoisko (2003) describes how an off-the-shelf system of a camera, microphone, and HMD can be used as a memory prosthesis. As people rely on the HMD for representing information, they may not feel a need to remember every detail.

## Knowledge

Knowledge is information in LTM and takes a variety of forms. For example, some visual information retains its spatial and temporal properties. Other visual information is converted in to a semantic form, where only the meaning of an event is recalled and not the specific details. Often a memory includes both types of information. Still other types of knowledge hold information about procedures and rules for behavior in specific situations.

### Visuospatial knowledge

Mental images are one example of visuospatial knowledge. If asked to count the number of windows in their house or apartment, many individuals will form a mental image of their house and (mentally) move from room to room and count the windows. This ability suggests that some information in LTM maintains the visual and spatial characteristics of the stimuli that engendered the knowledge.

Psychologists have discovered that these kinds of mental images have many of the properties and limitations of real images. For example, Shepard and Metzler (1971) asked subjects to look at a pair of block shapes similar to those in Figure 15-11. The shapes in Figure 15-11 a have the same structure, but one is rotated relative to the

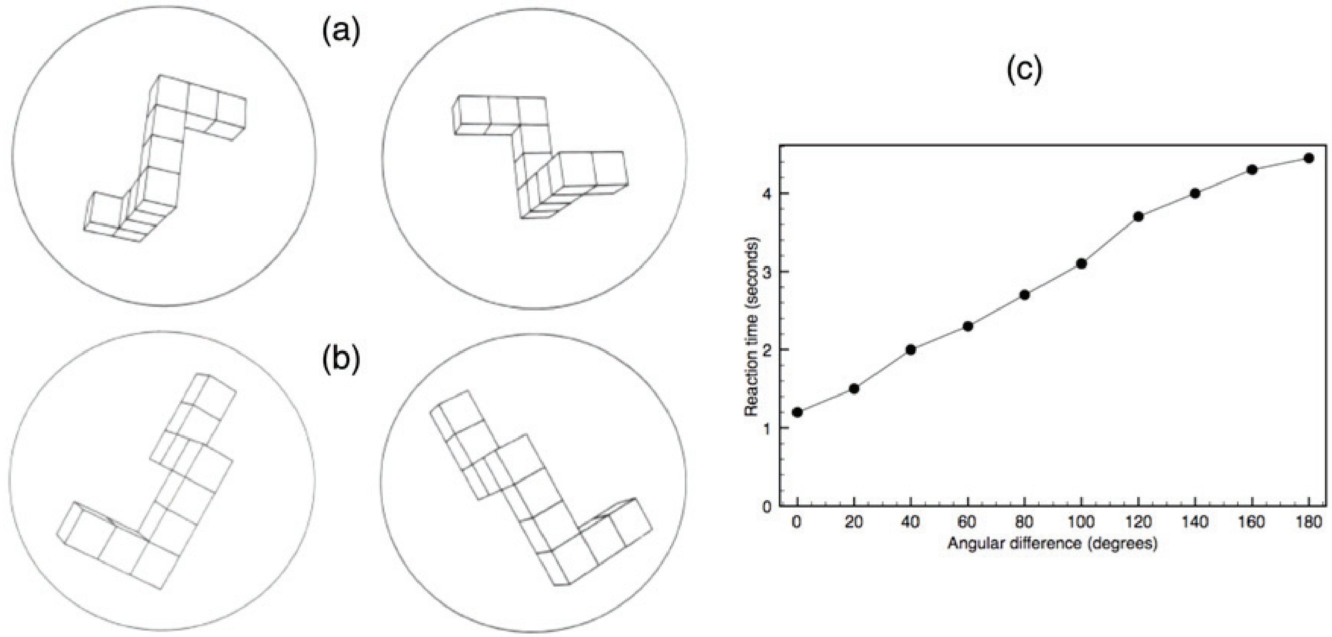


Figure 15-11. Stimuli and data for a mental rotation experiment (Shepard and Metzler, 1971). The shapes in (a) have the same structure, but one is rotated relative to the other. The shapes in (b) have different structures. The plot in (c) shows the reaction time for identifying same shapes as a function of the angular difference between the shapes.

other. The shapes in Figure 15-11b have different structures. For each pair the subject was to quickly decide whether the shapes were the same (but one rotated) or different. Many people report that they make their decision by mentally rotating one shape to match up with the other shape. Shepard and Metzler (1971) hypothesized that if the mental representation of the shape included the properties of a real image, then rotating a mental shape a given angle would require rotation through the intervening space as well. Thus, bigger angles of rotation should lead to longer delays before subjects make their decision. Figure 15-11c plots subjects' response time as a function of the angular difference between the two shapes. The results suggest that it takes about one second to rotate a shape through 50 degrees. Clearly there are similarities between the mental representation of these images and normal perception.

### Semantic knowledge

Semantic knowledge refers to representations of meaningful concepts and categories. The properties of mental concepts and categories are very important to understanding other aspects of cognition. If a person has knowledge that an animal they see is a cat, that person immediately has knowledge about the concept of cats that (probably) apply to this specific cat. Thus, a person can expect that the cat likes certain kinds of foods, has a certain type of relationship with people, catches mice, has teeth, and so on. All of this knowledge can be applied without much observation of this specific cat because the information is stored as a "cat" concept based on past experience.

Studies of semantic knowledge seek to understand how this past experience is represented as a concept. One key finding from cognitive science is that many mental concepts are based on a *prototype* element. A prototype is a standard representation of items corresponding to a concept or category. It is often a conglomeration of several different examples of a category. For example, the category "birds" corresponds to a prototype that is similar to a robin. Unusual birds such as penguins and ostriches are quite different from the prototypical bird. Consistent with this representation, individuals are much faster at classifying sparrows as birds than classifying penguins as birds (Rosch, 1975).

Rosch et al. (1976) argued that there are three levels of categories. The superordinate level refers to a broad class of everyday objects, such as a transport device. The basic level corresponds to items of common use, such as a tank (in military settings). The subordinate level corresponds to a still more specific type of item, such as an M1-A1 Abrams main battle tank. Basic level categories are hypothesized to have special status in knowledge systems. Individuals can categorize basic level items faster than items at the superordinate or subordinate levels. Not surprisingly, the basic level categories for an expert of a topic (say, a tank commander) would be different from the basic level categories for a novice (Tanaka and Taylor, 1991).

### Schemas

A schema is a cognitive structure that contains a sort of mental model of how the world operates within a particular situation. Schemas allow people to adapt to new situations by using knowledge about other similar situations.

If an American attempts to drive a car in the UK, the schemas involved in driving a car will both help and hinder his/her efforts. The schemas will help because nearly all cars work in a similar kind of way: turning the steering wheel changes the direction of the car, pushing the right most foot pedal accelerates the car, and so on. This kind of general knowledge transfers from one case (driving an American car) to another (driving a British car). The schemas will hinder because an American driver is used to driving on the right hand side of the road, while the British drive on the left hand side of the road. When pulling onto a road, an American driver has a tendency to immediately go to the right-hand lane, because the American driving schema indicates that this is the appropriate behavior.

Schemas are an integral part of daily life. When we encounter a new gadget and cannot figure out how to use it, the problem is usually that the way the device works is different from the schema we have in mind on how it should work. Thus, an important issue for HMDs is to insure that either the HMD is designed to match the schemas that people bring to the device, or that people can be trained to develop appropriate schemas for the device.

Along these lines, Yeh et al. (2003) investigated how people modified their attentional strategies as a function of the precision of a target cue. In their HMD a cue indicated a particular target for a user to focus on. Sometimes the cue precisely indicated where the target was located; other times the cue was less precise and only gave a general idea of where the target might be located. The precise and imprecise cues were drawn differently, so the subject could tell which precision condition they were operating with. Over time, the user developed schemas regarding how to behave with regard to these differing cues.

More generally, a user always adapts to the behavior of a system. Sometimes these adaptations are inconsistent with the expected uses of the system (Norman, 2002). An example related to HMDs involves head tracking. In some HMD systems the user's head is tracked and the image is updated appropriately to correspond to the head's orientation. In some cases, the system may appreciably lag behind the user's head movements. In normal environments, a person will make head movements in order to produce optic flow fields that contain information about the visual environment. If HMD latency interferes with the optic flow field, users will slow down their head movements in order to minimize this interference. Such a strategy involves creation of a new schema for how to extract information from the optic flow field.

There is no simple formula or rule that insures that a device's properties will match a user's schemas. The design of an HMD must include subject matter experts to understand what features the user needs and how to structure the user's interaction with the system.

## Decision-making

One of the benefits of HMDs is that the user has access to a vast amount of information. Such a benefit should enable the user to make better decisions. Indeed, making better decisions, such as how to fly an aircraft or identifying where the enemy might be located, is exactly what HMDs are intended to support. As for many other cognitive issues, until an HMD is put into use, there is no easy way to be certain that it will actually lead to better (or even good) decision-making.

There is often an implicit bias to believe that individuals are, or can be trained to be, rational decision makers. From this view, the goal of an HMD is to provide the best information so that individuals can make the best choices. However, this view is incorrect. While individuals can make rational decisions, rationalism is not always what guides decision-making behavior. It should be emphasized that this is not a matter of emotional biases undermining rationality. Emotions play an important role in decision-making by characterizing the value of different options and identifying what the decider *wants*. The problem is that people can have quite reasonable and consistent emotional judgments but still make non-rational decisions. We briefly discuss a few properties of human decision-making. There is nothing special about HMDs that would influence individuals to exaggerate many of these biases, but their existence may explain why individuals behave as they do. Further details can be found in Kahneman and Tversky (1982).

### Loss aversion

Individuals are generally more sensitive to the loss of a thing of value than to the gain of the very same thing. Most individuals will not take an even bet (e.g., a coin is flipped and if it comes up heads you win $5 but if it comes up tails you lose $5) because the possible loss is more aversive than the possible gain is alluring.

Loss aversion can have large impacts on an individual's behavior. For example, when choosing from a variety of possibilities that each contain positive and negative consequences, individuals tend to select the option that minimizes the perceived negative outcomes. Such a choice may not actually be the best decision, defined as giving the greatest satisfaction with the outcome.

Loss aversion can have very subtle effects on decision-making. Consider the following scenario:

> *Context A*: Suppose you are piloting a helicopter on a scouting mission. Your current position has an excellent view for observing enemy movements. However, there is a strong crosswind that pushes you uncomfortably close to trees. You decide that you need to find a new location and identify two possibilities:
>
> *Position 1*. Adequate view; little crosswind.
> *Position 2*. Good, but not excellent, view; moderate crosswind.

Most individuals will choose Position 2 rather than Position 1. The reason is found by comparing the gains and losses for the two choices relative to the current location of the aircraft. With Position 1 there is a substantial loss of view quality and a substantial gain in safety from the crosswind. Loss aversion makes the loss seem more important than the gain. For Position 2, there are similar gains and losses, but none are as extreme as for Position 1. A choice between the two positions tends to be dominated by a comparison of the relative losses. Position 1 involves more severe losses than Position 2, so most individuals prefer Position 2. The fact that Position 1 involves more gain than Position 2 is less important.

Now, consider a second scenario:

> *Context B*: Suppose you are piloting a helicopter on a scouting mission. Your current position has no crosswind, so it is relatively easy to avoid the nearby trees. However, the position provides a poor view for observing enemy movements. You decide that you need to find a new location and identify two possibilities:
>
> *Position 1*. Adequate view; little crosswind.
> *Position 2*. Good, but not excellent, view; moderate crosswind.

As in Context A, the decision-making process is dominated by the perceived losses of any potential switch. In this case, individuals tend to choose Position 1. The loss from the current location is relatively small (no crosswind to little crosswind). In contrast, Position 2 produces a larger loss (from no crosswind to moderate crosswind). The positions have similar effects on gains, with Position 2 having a larger gain than Position 1. But since losses dominate gains in decision-making, most individuals prefer Position 1.

Significantly, the two options are identical across both scenarios. For a rational decision maker, the current position of the helicopter should not make a difference in deciding between the two options. After all, the pilot wants to keep the aircraft safe and observe enemy movements. If the pilot is leaving the current position for a new one, it might seem that the properties of the current position are not relevant for judging which alternative is best. The conclusion is that humans are not rational decision makers.

### Comparing alternatives

When choosing from a variety of options, individuals tend to compare pairs of options against each other. When coupled with loss aversion effects, this can lead to very unusual behavior, where an option that no one ever selects dramatically influences other selections.

For example, consider the following two decision-making contexts:

*Context C*: Suppose you are piloting a helicopter back to an airfield. You need to return as quickly as possible, but you also need to minimize strain on the engine. Given the terrain, there are three possible routes:

*Route 1*: Little engine strain, 30 minutes.
*Route 2*: Little engine strain, 40 minutes.
*Route 3*: Moderate engine strain, 20 minutes.

Given such a scenario, most people quickly discount Route 2 because Route 1 is a better choice. It is less clear whether Route 1 or Route 3 is the best choice over all; it depends on the chooser's personal preference and (unspecified) details of the situation. Given this set of choices, most people chose Route 1.

Now consider a second decision-making context, which differs only in the nature of Route 2:

*Context D*: Suppose you are piloting a helicopter back to an airfield. You need to return as quickly as possible, but you also need to minimize strain on the engine. Given the terrain, there are three possible routes:

*Route 1*: Little engine strain, 30 minutes.
*Route 2:* Much engine strain, 20 minutes.
*Route 3*: Moderate engine strain, 20 minutes.

Once again, most individuals quickly discount Route 2, but this time because Route 3 is a better choice. Once again, it is less clear whether Route 1 or Route 3 is the best choice over all; it depends on the chooser's personal preference and details of the situation. However, given this set of choices, most people chose Route 3 rather than Route 1.

Thus, the properties of Route 2, which hardly anyone ever selects, can bias individuals to choose one of the remaining alternatives. It appears that the clear advantage of Route 1 over Route 2 in context C and Route 3 over Route 2 in context D biases the decider to prefer the option with the obvious advantage.

This effect has some important implications for decision-making while using HMDs. An HMD can display a wide variety of information, and adding information to an HMD can have an influence on decisions that might not be expected. The option to display information that no user would ever chose may, nevertheless, bias the user to make selections that are not necessarily optimal.

### Risk

When the choices available to people have probabilistic outcomes, they are making risky decisions. Individual's intuitions regarding the properties of probability are often incorrect, especially for small probabilities. Moreover, individuals deal with risk differently depending on whether the options available appear to be losses or gains. When the choices available to them are presented as gains or benefits, individuals tend to exhibit risk-avoiding behavior. For example, most individuals prefer option 1 from the following:

*Context E*: You are leading a group of 600 Warfighters after completing a mission when you suddenly spot a much larger group of enemy fighters. If you stay where you are, you will be overrun and everyone will die. Your advisors identify two possible choices of action:

*Option 1*: Take a route that will expose part of your group to enemy fire; the best estimate is that 200 Warfighters from your group will be saved.
*Option 2*: Take a route that has a 1/3 probability of having no one be detected by the enemy; thereby saving all 600 Warfighters. However, there is also a 2/3 probability that the enemy will detect everyone and no one will be saved.

Both choices have the same expected value (if repeated many times an average of 200 Warfighters would be saved), but for a particular choice, individuals tend to prefer option 1 with the certain saving of 200 Warfighters.

The situation is reversed for perceived losses. Here individuals tend to be risk-seeking.

*Context F*: You are leading a group of 600 Warfighters after completing a mission when you suddenly spot a much larger group of enemy fighters. If you stay where you are, you will be overrun and everyone will die. Your advisors identify two possible choices of action:

*Option 1*: Take a route that will expose part of your group to enemy fire; the best estimate is that 400 Warfighters from your group will be killed.
*Option 2*: Take a route that has a 1/3 probability of having no one be detected by the enemy; thereby none of the Warfighters will be killed. However, there is also a 2/3 probability that the enemy will detect everyone and all 600 Warfighters will be killed.

Once again, both choices have the same expected value (if repeated many times an average of 400 Warfighters would be killed), but for a particular choice, individuals tend to prefer option 2 with the possibility of none of the Warfighters being killed.

The results are interesting because the choices in the two situations are identical. With 600 Warfighters in the group, saving 200 Warfighters is the same thing as having 400 Warfighters killed. What is significant is that phrasing these options as gains (Context E) or losses (Context F) biases the decision-making of individuals.

Risk-avoiding and risk-seeking behaviors are not absolute rules of decision-making. Some individuals are more prone to take risks than others, and some individuals placed in Context C may decide to go with the second option. Nevertheless, these effects tend to bias individuals in a variety of important ways in many different contexts.

In the context of HMDs, these effects indicate that great care needs to be taken in how possibilities are presented to a user. If options are presented in a way that emphasizes the gains (benefits) of different possibilities, users will tend to make decisions in a way that avoids risk. On the other hand, when options are presented in a way that emphasizes the losses associated with different possibilities, users will tend to make decisions in a way that seeks risk.

## Problem solving

A problem to be solved refers to an obstacle between a present state and a goal that is not immediately obvious how to get around (Lovett, 2002). The ability to solve a problem is related to many previously discussed cognitive properties. Some problems are difficult because their solution requires keeping in mind more information than can be held by working memory. Other problems are difficult because loss aversion effects bias a person to consider only some types of possible solutions. Still other problems are difficult because a person lacks the appropriate schemas to characterize and analyze the important issues of a problem.

One important aspect of problem solving is to identify the differences between expert and novice problem solvers. Warfighters are specially trained for their duties, and are thus experts at solving certain types of problems. As a result of their training, experts in a particular field solve problems faster and with a higher success rate than novices. The key difference between expert and novice problem solvers seems to be that experts have schemas for solving problems that better fit their specialized topic area.

Experts generally have more knowledge about their field of specialization than novices. The knowledge they have is also organized differently than novices. In particular, experts often organize their knowledge in a way that indicates the fundamental aspects of solving a class of problems. One significant side effect of the differences between experts and novices is that an expert's problem solving ability tends to be restricted to a particular domain. When asked to solve problems outside of his or her area of expertise, an expert often does no better than novices (Bedard and Chi, 1992).

## Special Topics

### Human error

Reason (1990) describes several primary types of errors as corresponding to different cognitive stages. *Slips* and *lapses* correspond to errors in execution and/or storage of an action sequence. Here a person intends to perform an action but actually does something else. Errors of this type include forgetting to flip a switch, or shutting off the wrong engine during an emergency (Wildzunas, 1997). Slips and lapses usually occur when attentional resources are insufficient for a task or are overwhelmed by other events. For example, in the Three Mile Island accident the attentional system of a worker was overwhelmed by over 100 simultaneous warnings signals. *Mistakes* correspond to incorrect intentions or plans. Reason (1990) suggests that there are two types of mistakes, rule-based and knowledge-based. These correspond to the schemas and knowledge systems discussed above.

With advancements in technology, computer systems have replaced humans for many types of tasks. Such replacement can be beneficial because it removes the possibility for human error in a variety of circumstances. However, the computer system can only function within the range of situations that have been considered by its designers. When circumstances fall outside that range, it is necessary for a human to intervene. Significantly, the circumstances outside a device's range are inevitably situations where humans are not particularly adept at solving problems. If the problems could be easily characterized and solved, their solutions would have been built into the computer system. Thus, with advances in technology, people are increasingly asked to deal with situations for which they are not well suited. As mentioned previously, expert problem solvers are experts because they have experience and practice that create appropriate schemas to solve new problems. Errors in these kinds of systems generally occur because a sequence of unforeseen circumstances causes an unanticipated problem. There is no opportunity for an individual to become an expert at solving these kinds of problems, because the only crises that occur are those that cannot be practiced.

There are many other important issues that relate human error to properties of cognition and system management. Interested readers are advised to start with Reason (1990) for a useful introduction to the topic. Shappell and Wiegmann (2000) introduced the Human Factors Analysis and Classification System to characterize data at four levels of human-related failure: unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences. Each of these levels then expanded into a total of 17 causal categories that help identify how to address the appearance of error. For an example of how such a system applies to Army aviation, see Manning et al. (2004), who applied this system to an analysis of errors in military unmanned aerial vehicle accidents.

### Effects of stressors

Cognitive processes are influenced by a wide variety of factors. The descriptions of cognitive factors given above generally apply to many different situations. However, different subsystems for a cognitive process may respond differently to various stressful situations. For example, Walker et al. (2005) showed that sleep is necessary for information to be encoded in long term memory. Lack of sleep can lead to poor memory performance and skill acquisition (Walker and Stickgold, 2005). Lack of sleep also affects a variety of other cognitive and perceptual systems in aviation environments (Russo et al., 2005).

Working memory is sensitive to the presence of background noise, especially if it contains phonological information that interferes with the rehearsal of information in the phonological loop (Baddeley, 1986). Gomes et al. (1999) found that exposure to large pressure amplitude low frequency noise negatively impacted memory performance of aircraft technicians, but did not significantly affect performance on an attention task.

Lieberman et al. (2005) tested several aspects of cognition under combat-like stress. Their subjects were U. S. Army Rangers and U. S. Navy SEALS engaged in relatively brief, high-intensity training missions. As a result of the training, the subjects experienced sleep deprivation, high levels of physical activity, physiological, environmental, and psychological stress, and simulated combat activities. Lieberman et al. (2005) found that all cognitive measures showed a striking decrement compared to baseline measures. The cognitive functions affected included simple behaviors such as reaction time or vigilance and more complex behaviors such as memory and logical reasoning.

Chapter 16, *Performance Effects Due to Adverse Operational Factors*, discusses the effect of stressors on perception and cognition for HMDs in more detail.

## Situation awareness

Situation awareness (SA) refers to an internalized model of the current state of an environment. This internal model is believed to be the basis of decision-making, planning, and problem solving. Thus, any problems with SA will impact almost every other aspect of performance.

SA involves much more than simple perception of the world. Information in the world must be perceived, properly interpreted, analyzed for significance, and integrated with appropriate schemas that allow for a predictive understanding of the current state of the system, the system's likely future states, and appropriate behaviors from individuals within the system. A breakdown at any of the cognitive functions described above can contribute to a loss of SA.

Endsley (1999) suggests that SA involves three levels:

- Level 1: Perception of the elements in the environment: Important and relevant items in the environment must be perceived and recognized. This analysis includes elements in an aircraft (e.g., system status, warning lights) and elements external to an aircraft (e.g., other aircraft, terrain).
- Level 2: Comprehension of the current situation: Here the items from Level 1 are synthesized to produce a holistic representation of the environment. This type of synthesis requires background knowledge (schemas) that can interpret the Level 1 items to identify the relative importance of the system's current state.
- Level 3: Projection of future status: With sufficient comprehension of the system and appropriate understanding of its behavior, an individual can predict (at least in the near term) how the system will behave. Such understanding is important for identifying appropriate actions and their consequences.

In the study of Endsley (1999) perceptual issues accounted for around 80% of SA errors, while comprehension and projection issues accounted for 17% and 3% of SA errors, respectively. That the distribution of errors is skewed to the perceptual issues likely reflects the fact that errors at Levels 2 and 3 will lead to behaviors (e.g., misdirection of attentional resources) that produce Level 1 errors.

St. John et al. (in press) noted that SA is negatively affected by interruptions and multi-tasking. One of the difficulties of maintaining SA is to recover from a reallocation of cognitive resources as tasks and responsibilities change in a dynamic environment. In many respects, interruptions and multi-tasking introduce conditions for change blindness. To aid recovery of SA from these types of interruptions, St. John et al. (in press) proposed four principles on how to communicate changes in a system:

1. Automatic change detection: Since an individual will often fail to detect a change, the system should indicate when a change has happened.
2. Unobtrusive notification: An indicated change should provide information in a way that is available to the user, but not by forcing an interruption of its own (e.g., by not using a pop-up window that itself must be clicked away).
3. Overview prioritization: Changes should be listed in a way that allows the user to identify what kinds of changes are most important.
4. Access on demand: A user should be able to control how much change information is displayed.

The use of an HMD introduces both solutions and problems for SA. One the one hand, an HMD allows for information from new types of sensors and algorithms that can help guide the user's understanding of the environment. If organized properly, such information will tend to increase SA. On the other hand, if the information is organized improperly, this information will decrease SA. Moreover, even properly organized information can lead to a deterioration of SA if there is too much data. The National Research Council (1995), in an analysis of HMDs for the Land Warrior program, identified some of the cognitive factors and their potential benefits and costs with regard to SA. Table 15-2 describes the cognitive factors likely to be affected by HMDs and the benefits and costs of such effects with regard to SA.

What this analysis makes clear is that an HMD provides a rich set of possibilities for influencing SA, both positively and negatively.

## Cognitive workload

Cognitive (or mental) workload can be defined generally as the amount of cognitive processing that is required for an individual to perform a set of tasks at a given time. This is a concept that goes beyond the processing resources of cognition and is intimately related to desired performance. One cannot talk about workload unless one has a goal of what a person should accomplish. Attempts to define or study workload always have an implicit baseline of performance and attempt to identify the cognitive processes and limitations that influence performance. Workload affects performance by affecting response time (e.g., time to acknowledge and initiate a task), task completion time, throughput (how much work is accomplished during a period of time), and error rate.

Workload is both task-specific and individual-specific (Rouse et al., 1993). The amount of cognitive workload associated with a given task is affected by such factors as whether or not the task is internally (self) or externally paced, whether the task demand is constant or always changing, the presence of other simultaneous tasks, the level of consequences of task failure (internal stress), and the presence of external stressors (e.g., heat, cold, noise, etc.).

Scribner et al. (2007) measured workload in a task involving shot accuracy. They concluded that an HMD was not recommended for a shooting task because the display clutters the visual field and requires manual dexterity to interact with the display. They did note, however, that an HMD was well suited for other kinds of tasks.

Previously, attention was considered the single cognitive resource that had to be divided between multiple tasks (Wickens et al., 1988). Now, it is generally recognized that the extent to which multiple tasks can be performed simultaneously depends on whether they draw from the same resource (Navon and Gopher, 1979; Wickens, 1992; Harris and Muir, 2006).

Cognitive workload for specific tasks is measured by various approaches, including subjective ratings, analytic measures, task performance, physiological measures (e.g., heart rate, galvanic skin response, pupil diameter, blood pressure, and respiratory rate). One practical problem with the workload concept is that it is not precisely defined, and so different measures of workload do not necessarily agree with each other or tap into the effects that are fundamentally related to task performance.

Table 15-2.
Factors of HMDs affecting situation awareness.
(Based on Table 3-2 from National Research Council [1995])

| Factor | Benefit | Cost |
|---|---|---|
| Pre-attentive processing | Salient cueing of important information. | Distraction from critical environmental cues that may flag the need to fixate attention on the environment. |
| Attention | Cueing to attend to important information in HMD. | Limited attention degrades effective simultaneous intake of information through similar channels. |
| | Integration of HMD cues with external events providing information fusion. | Attentional narrowing under high task load or stress may result in fixation on displays, interrupting attention switching to environment. |
| | Expansion of area and time frame over which attention is distributed. | Trained information sampling strategies and scan patterns may be disrupted by stress and high task load. |
| | | Attention to some elements of situation may result in decrease in SA on other elements. |
| Working memory | Direct presentation of needed information may support limited working memory. | Extra cognitive tasks and task complexity imposed by system can seriously overload limited working memory, restricting SA and decision-making, particularly under stress. |
| | | Information overload may occur wherein the amount of information present exceeds the amount the user can take in, threatening appropriate prioritization of information. |
| Information | Provides more accurate, up-to-date information to soldiers in field, and back to headquarters from field. | Information overload will pose new sorting and processing demands. |
| | Provides information in a different format that may be more compatible with user needs. | Information presented that is not consistent with soldier needs will slow down processing of important information. |
| | Enhanced sensory information. | Information that must be integrated or processed to put in needed form will slow down processing. |
| | Provides more accurate information on location of self and others. | |

## Case Study 1: Hyperstereo Helmet-Mounted Displays (HMDs)

This chapter has described key perceptual and cognitive factors that are integral to human performance, frequently alluding to their relationship to HMDs. In this section, these factors are discussed as they apply to an HMD design approach that, while not new, is rapidly becoming a leading candidate for a number of programs that incorporate an HMD as the primary display.

The defining characteristic of this specific design approach is the movement of visual inputs from directly in front of the eyes to locations on the sides of the head/helmet. The motivation for this approach includes improved center-of-mass and expanded imagery capability. This new technology introduces a perceptual illusion called hyperstereopsis, where depth perception is dramatically modified.

In order to conduct operations 24/7 and in all-weather environments, militaries have adopted two major imaging technologies: image intensification ($I^2$) and thermal imaging (usually referred to as forward-looking infrared [FLIR]). These two technologies operate on different physical principles: $I^2$-based systems require a minimum level of ambient light and operate via the principle of light amplification (McLean et al., 1998); FLIR systems produce images of the outside scene by detecting small temperature differences between objects and the background (Rash et al., 1998). $I^2$ and thermal FLIR imagery offer the Warfighter views of the outside world that are substantially different from normal viewing and from each other. Each technology has its advantages and disadvantages and offers functional images of the outside scene under defined lighting and thermal environments.

$I^2$-based devices make up the most common night imaging technology within the military. While numerous variations in these devices exist, they are collectively referred to as night vision goggles (NVGs). NVGs are heavily utilized by dismounted and mounted Warfighters. The most currently fielded version of these devices is the Aviator's Night Vision Imaging System (ANVIS), which uses enhanced 3rd generation (GEN III+) image intensifier tubes (Figure 15-12, left). The U.S. Army's next most established HMD is the Integrated Helmet and Display Sighting System (IHADSS) fielded on the AH-64 Apache helicopter (Figure 15-12, right).

Figure 15-12. Pilots wearing ANVIS (left) and IHADSS (right).

An obvious approach for the next generation of HMDs is to provide Warfighters with the capability to view both $I^2$ *and* FLIR imagery, either in alternation (via selective switching) or as fused imagery, with the inclusion of symbology. In addition, recent advances in synthetic imagery make it desirable to have an HMD design that also allows its presentation.

However, while a host of optical issues must be addressed, any HMD designed to explore dual sensor (and synthetic) imagery presentations must still contend with the important biodynamic characteristics of head-supported weight and center-of-mass, as well as the conflicting optical requirements. It is mostly these concerns that have forced a decision between the two imaging technologies in the past.

Over the past two decades, in an attempt to improve center-of-mass, several HMD designs have been developed that move the $I^2$ sensors from directly in front of the eyes to positions on the sides of the helmet. Other proposed designs have coupled this relocation of the $I^2$ sensors with the added capability of presenting FLIR (and synthetic) imagery via miniature displays. One optical design accomplishes this by reflecting imagery off of the visor. The ability to provide the Warfighter with multiple versions of the outside scene is a leap in HMD design that could significantly improve user performance and situation awareness. A recent study investigating the use of both $I^2$ and FLIR sensors in the AH-64 Apache showed that each sensor provides unique capabilities (Heinecke et al., 2007).

Recognizing these advantages, virtually all of the major avionics manufacturers have explored this design approach. The majority of these efforts, although involving comprehensive developmental programs, never progressed to full production. Several of these manufacturers are already fielding HMD designs that relocate the $I^2$ tubes to the sides of the helmet and provide the capability of presenting both $I^2$ and FLIR imagery (as well as synthetic imagery). Most of these designs were first developed for fixed-wing applications. Kalich et al. (2007) summarize many of these hyperstereo designs. Two representative systems are the Integrated Night Vision System (INVS), which is built by Honeywell, Inc., Minneapolis, Minnesota, and commercially known as the Monolithic Afocal Relay Combiner (MONARC), and the TopOwl® system, which is manufactured by Thales, France. Each system is shown in Figure 15-13.

While improving center-of-mass issues and expanding imagery capability, these designs come with certain compromises. One perceptual consequence is a phenomenon referred to as "hyperstereo vision" or "hyperstereopsis" (see Chapter 12, *Visual Perceptual Conflicts and Illusions*). Stereopsis is a cue to depth perception based upon differences in the scene projected to the two eyes. The spatial separation of the eyes means that each eye has a slightly different view of the world. These differences lead to systematic shifts in image contours that correspond to items in depth relative to where the two eyes converge to a point of focus. The calculation of relative depth depends on the lateral separation of the eyes. In hyperstereo systems, the sensors receiving the visual information are placed substantially farther apart than the user's eyes. As a result, the image shifts across the two inputs are more substantial than for normal vision.

Figure 15-13. The MONARC (Honeywell, Inc.) (left) and the TopOwl® (Thales) (right) hyperstereo HMD designs.

Hyperstereopsis manifests itself as exaggerated depth perception, which is characterized by intermediate and near objects appearing closer than normal. At close distances (< 20 feet/6 meters), the ground appears to slope upward. Because the user's body and very nearby objects can be perceived under the goggles and by non-visual cues, a user sometimes experiences a "crater" effect, where the ground seems to rise up to chest level. Hyperstereopsis effects weaken for much longer distances because objects at longer distances introduce very small differences between the two eyes and sensors.

Hyperstereopsis effects are particularly problematic in the rotary-wing environment, where the most critical maneuvers are performed at very low altitudes and near the ground. For example, a pilot will perceive the near ground as rising up. When a helicopter pilot is sitting in the aircraft on the ground, it will look as if the ground level outside the cockpit is at chest level, causing some pilots to say it looks like they are sitting in a hole (Figure 15-14). However, distant objects will appear normal.

Figure 15-14. Depiction of illusion of ground position due to hyperstereo vision. The lines represent the level of the ground as perceived by the pilot.

Hyperstereopsis can also affect other aspects of perception. Objects can appear to be closer than reality and horizontal motion can be exaggerated. The horizontal and oblique velocity and acceleration vectors will be distorted differently, making shipboard landings, nap-of-the-Earth (NOE) flight, quick-in/quick-out maneuvers, motion parallax, and flow-field interpretation problematic. It likely will be very difficult to train for dynamic environments that involve the avoidance of obstacles near the helicopter.

The effects of hyperstereopsis need not always be negative. Some atypical hyperstereo configurations (based on camera pairs with extremely wide baselines or temporal delays with a single camera) have been investigated for their possible use in aerial search and rescue, target detection, and traversing drop-off terrain tasks (e.g., Cheung and Milgram, 2000; Schneider and Moraglia, 1994; Watkins 1997). And, as presented above, hyperstereo HMD designs allow for added operational capability by allowing the option of adding FLIR and synthetic imagery presentation.

Aware of the hyperstereopsis issue, the French, German and U.S. militaries have evaluated and conducted a number of limited operational evaluations on several of these designs in an attempt to determine its impact on performance (German Air Force Test Center, 1998; Kimberly and Mueck, 1991; Krass and Kolletzki, 2001; Leger et al., 1998). These studies primarily have investigated pilot performance and have resulted in mixed findings. Consistently, the reported hyperstereo effects were characterized by intermediate and near objects appearing distorted and closer than normal. The ground appeared to slope upwards towards the observer and regions beneath the aircraft appeared closer than normal; a tendency to fly higher than normal during terrain flight was noted.

The designers of these systems claim that users can “overcome” or “train out” the hyperstereo effects. The fielding of the Thales TOPOWL® hyperstereo HMD systems by the French and German armies supports this claim. A threshold period of 8-10 hours has been suggested (Kalich et al. 2007). However, the HMD community, collectively, has not fully accepted this position.

An underlying issue in “overcoming” the perceptual effects associated with the use of hyperstereo HMDs is whether this is achieved through perceptual adaptation or cognitive compensation. Perceptual adaptation refers to changes in perceptual experience. If users actually adapt to the use of a hyperstereo HMD, then they would eventually perceive the world to be at the veridical depth (i.e., coinciding with reality). In contrast, cognitive compensation implies that the world looks non-veridical but users develop strategies for successfully interacting with the modified appearance.

Studies that may be relevant to this adaptation vs. compensation conundrum are those that have investigated the use of prisms and mirrors to manipulate and produce unusual visual inputs. In these studies, images were shifted or inverted on the retina, producing a stimulus effect on the visual system not too dissimilar from systems that produce hyperstereopsis. These studies show that initially these changes cause major disruptions in visual-motor coordination and visual perception, followed by gradual "adaptation." This alleged adaptation is accompanied by a performance recovery that approaches, but does not equal, premodification performance (Welch, 1986; Wildzunas, 1997a). Most of these studies have involved tasks such as walking, ball tossing and other close-in eye-hand coordination activities. However, none of the studies involved tasks and working distances that are congruent with those associated with helicopter flight (CuQlock-Knopp et al., 2001; Judge and Bradford, 1988; Wildzunas, 1997b). Notably, these studies do not usually distinguish between perceptual adaptation or cognitive compensation, as either adjustment would lead to improved performance in a variety of tasks.

However, there is at least one scenario where there is strong evidence that perceptual adaptation can occur. When new glasses are prescribed, moderate levels of distortion may be present. But after a period of time, the wearer adapts and perceives the world as normal. In contrast, Lindin et al. (1999) analyzed the effects of wearing inverting prisms and determined that subjects did not "see" the world as "up-right;" rather, they learned to compensate for the inversion. This implies that major changes in the visual image are dealt with through cognitive compensation rather than perceptual adaptation.

Studies that have investigated hyperstereo in real aviation environments have not attempted to differentiate between adaptation and compensation. With few exceptions, most military investigations have been trial flights or flight tests with an engineering emphasis (German Air Force Test Center, 1998; Kimberly and Mueck, 1991; Krass and Kolletzki, 2001). Consequently, while hyperstereo HMD designs have been available for several decades, and several of these systems have been flight-tested, the high cost of flight tests has limited the study of long-term visual effects, especially the determination of an adaptation performance curve. This lack of data has prevented gaining a good understanding of whether the change in depth perception can be adapted to, or compensated for, with increasing exposure, which is critical to establishing sufficient training requirements of these systems.

However, in a joint flight study between Canada, Australia and the United States, conducted in August 2008, but not yet reported, pilot interviews following an average cumulative flight time of 9 hours using the Thales Aerospace TopOwl™ HMD, indicated that some level of adaptation to the hyperstereo effect may be achievable. With the exception of within 2-3 feet of the aircraft, the previously described "hole" effect seemed to no longer be experienced. This is a promising finding, but final analysis of the data has not been completed.

Identifying the mechanisms responsible for improved use of a hyperstereo system is important because the two possibilities have different implications and limitations. If users perceptually adapt to the changes in the visual image, then they would be able to operate with the system in virtually any situation. At the same time, switching from using the system to not (and vice-versa) may require some time for perceptual adaptation to take effect. Thus, transitions from normal vision to a hyperstereo system may be particularly important. Notably, if performance is based on perceptual adaptation, influence of memory, attention, and knowledge organization are unlikely to be a key part of these transitions.

In contrast to perceptual adaptation, if improved performance is due to cognitive compensation, then users have learned to change their behavior in response to perceptual experiences that they recognize as being different from normal. This strategy means that novel situations may not be dealt with properly because users have not learned the appropriate type of compensatory response. It might also be expected that with cognitive compensation a user can fairly easily transition between use and non-use of a hyperstereo HMD because all that changes are the schemas for operating with the system. Notably, if performance is based on cognitive compensation, transitions between normal and hyperstereo systems will be strongly dependent on the properties of memory, attention, and knowledge systems.

This case study emphasizes that an understanding of perceptual and cognitive systems are critical for judging the usability of systems such as HMDs that modify how humans interact with the outside world.

## Case Study 2: The Integrated Helmet and Display Sighting System (IHADSS)

This second case study discusses some of the perceptual and cognitive issues associated with the Integrated Helmet and Display Sighting System (IHADSS) (Figure 15-15). This system, the U.S. Army's only fielded integrated HMD, is flown on the AH-64 Apache attack helicopter, and has been field-tested and used by over seven countries.

The IHADSS presents both pilotage visual imagery and aircraft flight symbology (e.g., airspeed, altitude, and heading) to the pilot. Pilotage imagery originates from a nose-mounted forward-looking infrared (FLIR) sensor known as the Pilot's Night Vision System (PNVS). This sensor is located approximately 9 feet (3 meters) forward of and 3 feet (1 meter) below the pilot's eye position.

The IHADSS consists of a miniature, 1-inch diameter, cathode-ray-tube (CRT) and an optical relay assembly, the Helmet Display Unit (HDU) (Fig. 15-16). The electronic image of the external scene is captured by the FLIR sensor and through a series of processes is presented as a luminance pattern image on the face of the CRT. This image is relayed optically through the HDU and reflected off a beamsplitter, also known as a combiner, into the pilot's eye (Rash and Verona, 1992). (See Chapter 3, *Introduction to Helmet-Mounted Displays,* for a more complete description of the IHADSS).

The pilotage imagery is presented monocularly (right eye only). The pilot's unaided (left) eye is available for viewing cockpit panel-mounted displays, reading maps, and observing lights, flares, and enemy fire outside the cockpit. This situation of presenting separate images to each of the two eyes is referred to as dichoptic viewing, a condition considered in the early design phases of the IHADSS as a potential source of visual problems.

Figure 15-15. The Integrated Helmet and Display Sighting System (IHADSS).

The HMD is designed so the image of the 30° vertical by 40° horizontal field-of-view (FOV) of the FLIR sensor subtends an identical 30° x 40° FOV at the pilot's eye. This provides unity magnification, which is necessary for piloting the aircraft. At nighttime, the pilot flies the aircraft using predominately the sensor imagery presented exclusively to the right eye via the HDU.

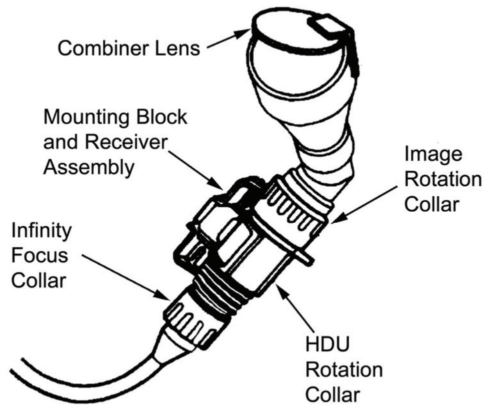


Figure 15-16. The Helmet Display Unit (HDU).

The AH-64 attack helicopter with its FLIR sensor and IHADSS HMD is a very challenging aircraft to fly. The pilot is expected to control and fly this tremendously sophisticated piece of machinery and perform combat missions using a reduced FOV picture of the outside world that is presented with visual cues from a completely different spectral range. The human visual system is designed to process information from natural visual scenes, but the IHADSS FLIR-based imagery is far from natural. In addition, the quality of the HMD imagery often is severely degraded in both contrast and resolution. As a result, this imagery has great potential to be misperceived (or misinterpreted).

In this section we consider several perceptual and cognitive issues that either are, or were expected to be, problematic for the use of the IHADSS. As part of this analysis, we try to highlight those perceptual and cognitive components that are likely to play a significant role in the use of the IHADSS. While this discussion focuses on real and potential problems with the IHADSS, this is not intended to undermine the many positive characteristics of the system. The IHADSS FLIR-based imagery provides information and opportunities for pilots to perform missions in situations that would otherwise be unmanageable, and as such is an enabler of missions, albeit with obviously increased risk compared to more normal conditions.

## Depth perception

The IHADSS degrades a variety of visual cues for spatial depth. The most obvious missing cue is the loss of binocular stereopsis. The scene on the IHADSS display typically does not correspond to the scene for the unaided eye. As a result, the different views available to the two eyes do not contain the disparity cues that are normally used to judge relative distances of objects. The disparity cues that support stereopsis are most effective up to about 30 meters (100 feet) (Cutting and Vishton, 1995); a range that is quite important for tactical helicopter flight.

Fortunately, monocular cues to depth such as retinal size, occlusion, motion parallax, and perspective, generally provide cues to relative depth that compensate for the absence of the normal binocular disparity cues. This is easily verified by noting that the visual world does not appear flat when you close one eye. However, other aspects of the IHADSS can degrade some of these monocular cues as well.

The monocular cue of retinal size can be used to judge relative depth if the object is recognized and can be compared to its reference size in memory. The reduced resolution of the FLIR sensor/IHADSS display means that the visible scene lacks the crispness and detail of normal vision and it may be difficult to use the retinal size cue in some situations. Occlusion cues refer to the fact that parts of a closer object can cover and conceal parts of a farther object. Such cues will still be present in an IHADSS image, but their effectiveness may be reduced by the limited FOV. In general, a larger view of the scene will provide more information about the relative depths of objects in the scene. Perspective cues (which are based on changes in light as it passes through the atmosphere) may be entirely absent in FLIR imagery. Motion parallax refers to the fact that nearby objects will appear to move faster than farther away objects. In normal viewing, individuals often move their heads to produce these motion cues and thereby judge relative depth. Such efforts may be difficult in the IHADSS because there is a lag between the user's head movement and the system's updated imagery. Overall, AH-64 pilots have reported a reduction in monocular cues; most likely due to the reduced resolution of the FLIR sensor/IHADSS display (Crowley, 1991; Hale and Piccione, 1989).

During development of the IHADSS, there was substantial concern that the IHADSS' monocular design would produce a depth-related phenomenon known as the Pulfrich effect. The Pulfrich effect occurs when both eyes view the same scene but one eye receives a higher level of light intensity than the other eye. This intensity difference leads to an interocular difference in the time needed for neural signals to reach those areas of the brain involved in depth perception. Thus, the intensity difference can lead to something similar to the motion parallax cues. The effect is that an object moving in a frontal plane appears to move out of the plane and approach toward or recede from the viewer. The difference in intensity could occur in two situations with the IHADSS. First, in nighttime viewing, the FLIR imagery may reveal the same objects and contours that are visible to the unaided eye, but at a higher intensity. Second, during daytime viewing the IHADSS monocle provides see-through capability, but is tinted to insure that symbology and other information is visible. This tinting means that the unaided eye views objects and contours with a higher intensity than the aided eye.

Despite these concerns, pilots have not reported experiences that would be consistent with the presence of the Pulfrich effect (Rash, in press). For nighttime viewing this can be explained by the fact that the two eyes rarely see the same scene. The unaided eye usually views the interior of the cockpit, while the aided eye views the FLIR imagery of the outside world. Thus, there is no opportunity for the information from the two eyes to combine and produce an illusory depth experience. It is less clear why the Pulfrich effect does not occur during daytime viewing, but perhaps the tint of the lens is not strong enough to produce the effect (Lit, 1949), or because most scenes have other depth cues that work against the effect.

One remaining influence on depth perception is the position of the PNVS sensor on the aircraft. Interpretations of unaided vision are tightly tied to the position of the eyes on the head. When flying the AH-64, the primary visual input for night and foul weather flight is the PNVS sensor. This sensor is located in a nose turret approximately 9 feet (3 meters) forward and 3 feet (1 meter) below the pilot's design eye position (Figure 15-17). Such positioning has the advantage of providing an unobstructed view of areas below the physical aircraft, which is definitely useful when landing in cluttered areas. On the other hand, this exocentric positioning of the sensor can introduce problems of parallax, motion estimation, and distance estimation (Hale and Piccione, 1989). Pilots also must learn how to manipulate the aircraft from a point of view that is different than their visual system is used to. Such learning faces issues similar to those involved in learning to fly with a hyperstereo system, as described above.

### Binocular rivalry and attention switching

As discussed above, the monocular display format of the IHADSS means that the two eyes often view different scenes. If the two scenes are dramatically different and do not allow for an interpretation of a scene in depth, the percept tends to be related to only one scene, with the view in one eye suppressing the other (Bishop, 1981). This type of binocular rivalry was one of the biggest concerns about the development of the monocular IHADSS (Rash et al., 2008).

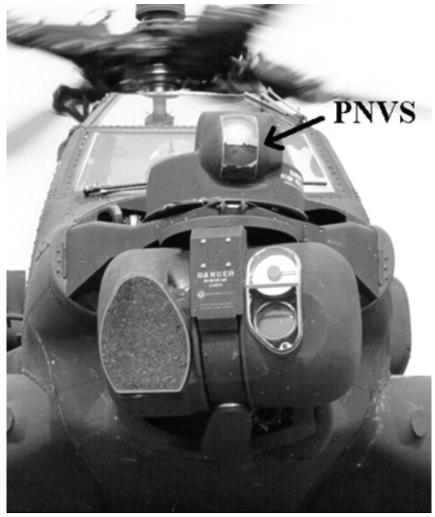


Figure 15-17. The position of the Pilot's Night Vision System (PNVS) and other imaging systems on the nose of the AH-64.

A variety of factors are known to influence binocular rivalry including brightness, timing, spatial detail, and color differences. For example, the relatively bright green phosphor in front of the right eye can make it difficult to attend to a darker visual scene in front of the left (unaided) eye. Conversely, if there are bright city lights in view, it may be difficult to shift attention away to the right (HDU) eye (Hale and Piccione, 1989). AH-64 pilots report occasional difficulty in adjusting to one dark-adapted eye and one light-adapted eye (Crowley, 1991). Most pilots have developed strategies to overcome rivalry effects (Rash, 2000).

While attentional focus can influence binocular rivalry (Chong et al., 2005) it is not the only important factor. In some situations, efforts to attend to items in one eye have only a slight effect on preventing a "flip" to the other eye (Meng and Tong, 2004). Such flips can be especially dangerous when a pilot tries to acquire information with one eye, but the scene from the other eye intrudes. For example, it may be hard to read instruments or maps inside the cockpit with the unaided eye, because the IHADSS eye "sees" through the instrument panel or floor of the aircraft, continuously presenting the pilot with a conflicting outside view. In addition, attending to the unaided eye may be difficult if the symbology presented to the right eye is changing or jittering (Crowley, 1991).

Moreover, attention switching between the eyes can be difficult, particularly as mission time progresses (Bennett and Hart, 1987). Some pilots resort to flying for short intervals with one eye closed, which is extremely fatiguing (Bennett and Hart, 1987; Hale and Piccione, 1989). User surveys indicate that the problems of binocular rivalry tend to ease with practice, but that rivalry is a recurrent pilot stressor, especially during a long, fatiguing mission and when there are other difficulties such as problems with display focus, flicker, or poor FLIR imagery (Bennett and Hart, 1987; Hale and Piccione, 1989).

More generally, these types of systems are, in principle, susceptible to the change blindness and cognitive tunneling phenomena discussed previously. It is difficult to attend to multiple scenes, and important information may be missed while attention is focused elsewhere.

Future designs of these kinds of systems may introduce even more opportunities for binocular rivalry. The design for the next generation U.S. Army helicopter calls for the integration of FLIR and $I^2$ sensor imagery. Due to the weight and size characteristics of FLIR technology, the FLIR's position will remain exocentric. However, the $I^2$ sensor(s) has two location options. It may be collocated with the FLIR sensor on the nose of the aircraft, or it may be helmet-mounted. If both sensors are exocentrically located, only the basic concerns of this mode of location, as listed above, require consideration. However, if the $I^2$ sensor is helmet-mounted, there may be problems associated with the mixed location modes and the resultant switching of visual reference points.

## Head movement strategies

By virtue of their design, HMDs are mounted totally, or in part, on the user's helmet. In the IHADSS, the display section is helmet-mounted. The sensor section is nose-mounted on the aircraft and is integrated with the helmet in such a way that head movements control the direction of the sensor's line-of-sight. While head movements are a natural part of normal viewing, eye movements are also an important part of natural viewing, but eye movements are not captured and used with the IHADSS. Eye movements can be used to focus on particular parts of the IHADSS display, but, unlike normal vision, the external visual scene does not change in response to an eye movement.

Helmet-mounted imaging systems, such as the PNVS/IHADSS, use the pilot's head as a control device. Head position is employed to produce drive signals that slave the sensor's gimbaled platform to pilot head movements. Infrared detectors mounted on the helmet continuously monitor the head position of the pilot. Processing electronics of the IHADSS convert this information into drive signals for the PNVS gimbal. This type of control system is called a visually coupled system (VCS). It is a closed-loop servo-system that uses the natural visual and motor skills of the pilot to remotely control the pilotage and targeting sensors and/or weapons.

One important operating parameter of VCSs is the sensor's maximum slew rate. The inability of the sensor to slew at velocities equal to those present in unrestricted pilot head movements would result in 1) significant errors between where the pilot thinks he is looking and where the sensor actually is looking and 2) time lags between the head and sensor lines-of-sight. Medical studies of head movements have shown that normal adults can rotate their heads +/-90 degrees in azimuth (with neck participation) and -10 to + 25 degrees in elevation without neck participation. These same studies showed peak head velocity is a function of movement displacement, i.e., the greater the displacement, the greater the peak velocity, with an upper limit of 352 degrees/second (Alien and Webb, 1983; Zangemeister and Stark, 1981). However, these studies were laboratory-based and do not reflect the velocities and accelerations indicative of a helmeted head in military flight scenarios. In support of the AH-64 PNVS development, Verona et al. (1986) investigated single pilot head movements in an U.S. Army JUH-1M utility helicopter. In this study, head position data were collected during a simulated mission where four JUH-1M pilot subjects, fitted with a prototype IHADSS, were tasked with searching for a threat aircraft while flying a contour flight course (50 to 150 feet [15 to 46 meters] above ground level). The acquired head position data were used to construct frequency histograms of azimuth and elevation head velocities. Although velocities as high as 160 and 200 degrees/second in elevation and azimuth, respectively, were measured, approximately 97 percent of the velocities were found to fall between 0 to 120 degrees/second. This conclusion supported the PNVS design specification of a maximum slew rate of 120 degrees/second. It also lends validity to pilot complaints that the target acquisition and designation system sensor (with a maximum slew rate of 60 degrees/second) is too slow.

Even in the IHADSS, there are anecdotal reports that pilots complain they must slow down their head movements to effectively use the system. The problem seems to be related not to the slew rate of the PNVS, but to a lag for the system to detect changes in head acceleration (e.g., to start and stop a movement). Some lags are inevitable in a system, such as the IHADSS, where the FLIR sensor is physically separated from the head. In the IHADSS the VCS must continually calculate the user's head position, translate it into sensor motor commands, and route a command to the sensor gimbal; the gimbal must move the slew to the new position; finally, the display must be updated with a new image. Lags of this sort can produce a variety of deficits and image artifacts (Moffit, 1997; Kalawsky, 1993; Biocca, 1992). It appears that pilots have learned how to minimize these problems by restricting their head movements to fit within the limits of the system.

Head movement strategies are particularly important in the IHADSS (and most HMD systems) because the system provides a greatly restricted field of view (FOV) of a visual scene, as schematized in Figure 15-18. FOV in the IHADSS system is limited by two primary factors. The first factor is the weight of the helmet. A larger FOV invariably leads to larger optics and more weight. The second factor is the FOV of the sensor. For piloting an aircraft, the FOV of the sensor needs to be mapped with no change in magnification to the HMD display (else image quality quickly deteriorates).

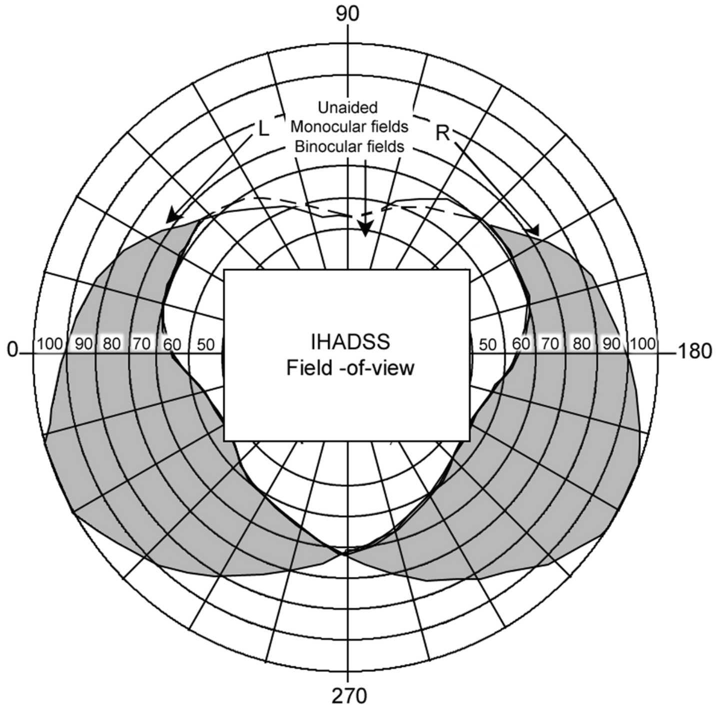


Figure 15-18. Pictorial representation of the IHADSS' 30- x 40-degree field-of-view as compared to that of the normal human field-of-view.

There are two aspects of the sensor's FOV. The first aspect is the amount of the visual field that can be covered in a single image. This is largely limited by the physical properties of the sensor. As shown in Figure 15-18, the IHADSS' 30 x 40 degree FOV appears small when compared to the FOV of the unaided eye. However, this reduced size is not so significant when one considers the multiple visual obstructions (i.e., armor, support struts, glare shield) that are normally present in military aircraft (Rash et al., 1990). With its external placement, the PNVS avoids many of these obstructions. The second aspect of FOV is the range of movement for the sensor. The IHADSS system provides an unimpeded external view throughout the range of the PNVS' movement (+/- 90 degrees in azimuth and +20 to -45 degrees in elevation).

As with pilots flying NVGs, AH-64 pilots are trained to use continuous scanning head movements to compensate for the limited FOV. Potentially disorienting effects occur when the pilot's head movements exceed the PNVS' range of movement. When this happens the head continues moving but the image remains unchanged. This situation could be misinterpreted by the pilot as a sudden aircraft pitch or yaw in the opposite direction of the head movement.

Not all of the effects of reduced FOV on pilot performance are fully understood. The task of determining a minimum FOV required to fly is not a simple one. The minimal FOV required is highly task-dependent. A high-speed flight across a desert floor with few obstacles can be accomplished with sensory cues that can be identified with a rather narrow FOV. On the other hand, performing a hovering turn in a confined area can only be accomplished with visual cues that need a wide FOV. Similarly, information is not processed equally across a display. Very fine visual details are only effectively processed for the parts of the display that fall on the fovea of the eye. Expanding the FOV to include more periphery information would not likely provide any benefit for some fine discrimination tasks, although eye movements across the display complicate matters substantially.

FOV problems in IHADSS are further complicated by the dual use of the IHADSS display. It is used to provide a view of the external world through the PNVS and also to provide flight symbology. Fight symbology information is placed on the edges of the CRT display, so as not to interfere with views of the external world. However, by being on the edge of the display, the symbols are difficult to resolve without an eye movement to place the symbol image on the fovea of the eye. Such eye movements require planning and attention that distract from other flight duties. To avoid this problem, some AH-64 pilots use the CRT horizontal and vertical size controls to reduce the overall size of the image (Hale and Piccione, 1989). This allows the pilot to view all of the imagery and symbology without difficult eye movements. Critically, though, the PNVS' FOV now occupies less area on the combiner and no longer maintains an accurate angular size of the scene. Since this minified image can cause problems with distance and size perception, it is strongly discouraged.

## Interpreting sensor information

Normal vision has evolved to work with light energy over a specific part of the electromagnetic spectrum. As Figure 15-19 shows, the visible portion of this spectrum falls roughly between 400 and 700 nanometers (0.4 to 0.7 microns). Within this range, light behaves in certain ways as it reflects off of objects of different properties. Within the human visual system, different wavelengths of light that hit the eye are, to a first approximation, interpreted as different perceptual colors that identify properties of object surfaces. The visual system makes several assumptions about the properties of light and how it interacts with objects. For example, there is a bias to interpret illumination of a scene as coming from above (Ramachandran, 1988), which can have a strong effect on interpretations of cast shadows, relative depth perception, and figure-ground distinctions. Chapter 2, *The Human-Machine Interface Challenge*, discusses some other assumptions of perceptual and cognitive systems.

The images on the IHADSS that are generated by the PNVS do not necessarily obey the assumptions of the visual system. As Figure 15-19 shows, the PNVS thermal sensor captures electromagnetic energy from the infrared region with wavelengths between 8000 to 12000 nanometers. It is this ability to create images from long wavelength sources (heat energy) that allows the PNVS to provide nighttime vision. All physical objects emit some infrared energy. The PNVS sensors can detect emitted energy (of the right wavelength) from objects that are at temperatures of approximately -35 C° or higher. The IHADSS display shows a "heat map" of a visible scene.

Figure 15-20 shows a scene with a photograph taken by a normal (visible light) camera on the left and with an infrared camera on the right. There are many similarities between the two images. In each image, many of the major buildings are detected, and contrast between adjacent objects is notable. On the other hand, there are many significant differences in the two images. For example, the electrical wires visible in the normal image are almost invisible in the infrared image. Similarly, the writing on the railcars is visible in the normal image but washed out in the infrared image. The emissions from the buildings are nearly invisible in the normal image but are quite clear in the infrared image. Most of these differences are due to the properties of the sensors. They detect different types of electromagnetic energy and so are sensitive to different parts of the scene.

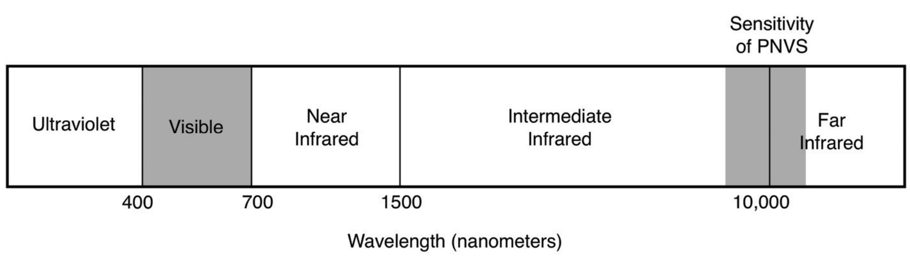


Figure 15-19. The electromagnetic spectrum. The gray areas indicate the wavelengths for normal vision and for the PNVS sensors.

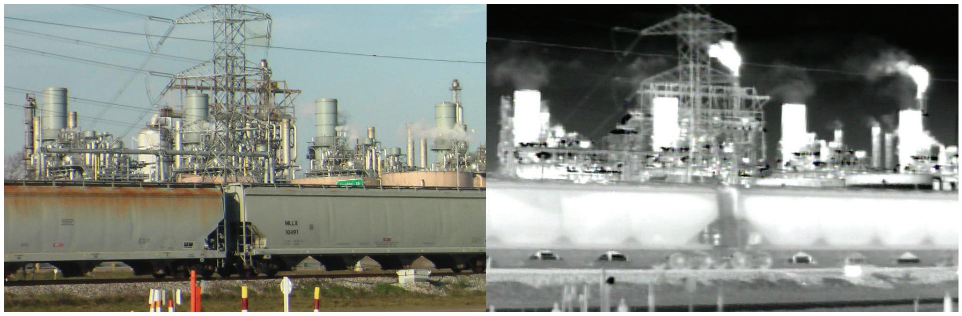

Figure 15-20. Pictures of a scene taken with a normal camera (left) and with an infrared camera (right).

One major difference from normal viewing of a scene is that the display is monochromatic in most devices. A normal image displays a variety of wavelengths of light that humans interpret as different colors. When printed on a black and white printer, both of the images in Figure 15-20 fail to show these colors. In the original (color) photo of the scene, wavelength differences allow a viewer to identify that the railcar on the left is rusty while the railcar on the right is not. Neither of the monochromatic images captures this difference and cannot distinguish the color differences of the railcars.

Using the PNVS requires learning how different surface properties correspond to different heat intensities. These relationships differ from those for light in the visible spectrum. Many surfaces that appear black in the visible spectrum may be very bright in the infrared spectrum. Likewise, surfaces that are bright in the visible spectrum may be relatively dark in the infrared spectrum (e.g., the sky in Figure 15-20).

The visual system's assumptions also can cause misunderstandings of an infrared image. For example, without the normal photo as a reference, the infrared image in Figure 15-20 does not seem to contain railcars at all. Instead, the cooler spaces between the wheels of the railcars appear to be some kind of bump (perhaps tents) in front of a wall. The railroad tracks appear to be another wall, perhaps in front of a body of water.

One challenge to learning how to interpret an infrared image is that the reflectance properties of surfaces depend on thermal properties that have unexpected consequences on the imagery. For example, twice a day (generally at midmorning and late afternoon) there is a thermal crossover, where temperature conditions are such that there is a near total loss of contrast between two adjacent objects in the infrared imagery. During this thermal crossover, the polarity of contrast reverses. In early morning the background temperature may be greater than a target's temperature, and the target will have a lower intensity on the infrared image. After thermal cross over, the target's temperature may be greater than the background and will have a higher intensity on the infrared image. Further, these attributes may change with the exposure history of the viewed objects, since objects will absorb more or less heat during the day depending on meteorological conditions. These are not changes that are easily interpreted by the human visual system, so they must be learned through cognitive strategies.

## AH-64 accident rate

Immediately following the initial fielding of the AH-64A (and the IHADSS), numerous anecdotal reports of various physical and psychological/sensory problems surfaced. Hale and Piccione (1988) conducted the first user survey of AH-64 pilots and found evidence of increased pilot fatigue and, predominate among other complaints, headaches. They cited as possible causes almost all of the IHADSS-related factors discussed above plus additional hardware design issues (e.g., inadequate eye relief) and overall discomfort. Over the next 25+ years of fielding, numerous user surveys have documented consistent, but varying, rates of fatigue and other symptoms generally attributed to the IHADSS HMD (Behar et al., 1990; Crowley, 1991; Rash et al., 2001).

Informally, there has been a long-standing question within the aviation community as to whether there may be a connection between AH-64 accidents and the use of the IHADSS HMD (in combination with the FLIR pilotage sensor). The investigation of such a possible role was the primary objective of a study by Rash et al. (2003). This study analyzed accident data obtained from the U.S. Army Risk Management Information System (RMIS) database that was created in 1972 and is maintained by the U.S. Army Combat Readiness Center (USACRC) (formerly the U.S. Army Safety Center), Fort Rucker, Alabama.

Each AH-64A/D accident between October 1985 and March 2002 was reviewed by a panel of vision scientists and pilots that assessed the role of the HMD and/or FLIR sensor in the accident. Out of the 98 accidents that used the IHADSS only 2 accidents were identified as having the IHADSS/FLIR as a major contributing factor to the accident (meaning that without this component, any other factors could have been overcome without mishap). Thus, one important conclusion from this study is that the IHADSS/FLIR is not a major factor in the vast majority of AH-64 Apache accidents. This finding suggests that despite the difficulties of using the IHADSS, pilots have adapted to the needs and limitations of the system to effectively fly their aircraft.

An additional 19 accidents were revealed to have the IHADSS/FLIR as a subsidiary component of the accident (meaning that other factors would have lead to an accident in any case, but the IHADSS/FLIR made the accident sequence more difficult to deal with or the outcome more severe).

Table 15-3 lists causal factors related to the IHADSS/FLIR that were involved in the 21 accidents where the system was a major or subsidiary component of the accident. Some accidents involved multiple factors, so the numbers do not add up to 21 accidents or 100%. The most frequent causal factor in all of the accidents studied was dynamic illusions (91%), with undetected drift being the most common type. As an example, in one accident, the aircraft was allowed to drift into a tree because the student pilot failed to adequately monitor instruments, and the instructor pilot misjudged the position of the aircraft in relation to the trees (height judgment, 24%).

The second most frequent causal factor was degraded visual cues (62%), which was distributed across multiple sub factors with poor FLIR sensor conditions (19%) and impaired depth perception (19%) being most common. This was exemplified in one accident where the crew was operating under poor FLIR sensor conditions (following 4 days of rain). While trying to maintain a hover, the poor FLIR sensor visual cues, in conjunction with a lack of depth perception, prevented the crew from detecting the presence of trees and aircraft drift. As a result, the main rotor blades made contact with the trees.

The presence and frequency of the causal factors in the AH-64 accidents studied are consistent with the findings of Crowley (1991) and Rash et al. (2001). Both studies listed pilot reported problems associated with dynamic illusions, particularly undetected drift. Hale and Piccione (1988) and Rash et al. (2001) also raised concerns about poor sensor performance.

The HMD accident study concluded that while the presence and use of the IHADSS HMD present a very unique situation in the AH-64 Apache cockpit, it does not seem to be a major contributor to accidents. However, the study did suggest that the use of the IHADSS HMD was one more factor that increases workload and requires increased crew coordination. The study also concluded that the inability of the legacy FLIR sensor performance to provide pilots with sufficient resolution had an impact on safety. This poor performance is greatly increased during and following periods of environmental conditions that render the FLIR sensor ineffectual. The resulting lack of image quality significantly increases visual workload.

## Applying Knowledge about Cognition to HMD Designs

The field of cognitive science has identified many aspects of cognition that are relevant to the development and use of HMDs. Indeed, HMDs provide such a rich variety of stimuli in challenging and important situations that they tap into properties of nearly every cognitive system. An understanding and appreciation of the properties of these cognitive systems will help focus designer and user expectations on what can and cannot be accomplished with HMDs.

Table 15-3.
Summary of accident factors (Rash et al., 2003).

| Accident Factor | Number of accidents where factor was present or contributing | Totals (%) by accident factor |
|---|---|---|
| **Display-related** | | **7 (33%)** |
| -Physiological causes | 0 | |
| -HDU impact on visual field | 1 | |
| -Alternation/rivalry | 1 | |
| -Degraded (insufficient) resolution | 5 | |
| **Degraded visual cues** | | **13 (62%)** |
| -Poor FLIR conditions | 2 | |
| -Loss of visual contact with ground | 2 | |
| -Impaired depth perception | 4 | |
| -Limited FLIR sensor FOV | 1 | |
| -Inadvertent IMC | 2 | |
| **Static illusions** | | **5 (24%)** |
| -Faulty height judgment | 5 | |
| -Trouble with lights | 0 | |
| **Dynamic illusions** | | **19 (91%)** |
| -Undetected drift | 11 | |
| -Illusionary drift | 0 | |
| -Faulty closure judgment | 5 | |
| -Disorientation (vertigo) | 3 | |
| **Hardware-related problems** | | **10 (48%)** |
| -FLIR sensor failure | 5 | |
| -IHADSS display/HDU failure | 0 | |
| -Design limitation | 5 | |
| **Crew coordination related to IHADSS/FLIR sensor** | 12 | **12 (57%)** |

## The problem with guidelines

It is common at the end of a chapter such as this one to provide a list of guidelines for designers to follow as they build and test HMDs (National Research Council, 1995, 1997; Patterson et al, 2006; Wickens et al., 1998). We are resisting the urge to create this kind of list because we do not feel that such guidelines are actually very useful in their current forms. Instead, we want to look at why these kinds of guidelines are not particularly useful and identify how information from cognitive science could be used in a different way.

To illustrate some of the problems with guidelines, consider a commonly cited guideline (e.g., Holley and Busbridge, 1995; Svensson et al. 1997):

- *Avoid overtaxing the user's short term memory capacity. Chunk items together so that a user does not have to remember more than seven items.*

The reference to seven items refers to a classic cognitive psychology paper by Miller (1956) that reported that individuals could remember (on average) about seven items for immediate recall (also see Figure 15-4). Longer lists of items produced some forgetting. The guideline is certainly correct that some environments can overtax a user's memory; however, there are several problems with this kind of guideline.

1. The implied statement in the second sentence is out of date. Miller's paper was a breakthrough finding at the time, but in the intervening 70 years the seven-item limit has been shown to be wrong. The number of items that can be kept for immediate recall varies dramatically. For items that sound very similar it is often much less than seven items (Conrad and Hull, 1964). With substantial amounts of training, some individuals can learn to use long term memory for immediate recall, and can recall lists of nearly 100 items (Chase and Ericsson, 1982).
2. Even if the second part of the statement were true, it is not clear how to satisfy the guideline. In particular, what counts as an *item*? Is a word a single item, or is it made of items defined by letters, syllables, or phonemes? Without a way to count the number of items it is impossible to determine if a task is over the user's limit.
3. The guideline does not make sense in isolation and cannot be treated as absolute. There may be some tasks where overtaxing the user's memory is not a problem. In particular, if information is displayed visually, a user can simply refer back to the display to examine information that might be forgotten. There may be some contexts in which this guideline is important, but the guideline itself cannot (and does not) indicate when it is important.
4. Satisfying this particular guideline can introduce a display that violates other guidelines. One way to avoid overtaxing short term memory might be to keep all necessary information visible on a display. But then the user must select which information should be displayed and must search the screen for the particular information needed. These new requirements probably violate other guidelines. It is not at all clear which guideline should dominate when several guidelines conflict with each other.

The second and fourth criticisms apply to most guidelines. Human cognition is sufficiently complex that it is very difficult to predict what a person will do in any specific circumstance. By their very structure, guidelines can only give general suggestions about what a designer should consider.

As a second example, the National Research Council (1997) analyzed HMDs for the Land Warrior System. The end of almost every chapter includes design guidelines. The executive summary emphasized four guidelines (page 6):

1. Minimize the degree to which the display is a physical barrier to acquiring information about the environment.
2. Provide integrated information in a task-oriented sequence, minimizing extraneous information and memory requirements.
3. Use graphics that have been well learned by the soldier. Simplify the presentation of data entry and system control options.

At first glance, these all seem like reasonable guidelines for an HMD design, but careful thought reveals that they are not really guidelines but *goals*. A guideline should indicate how to build a system, but these "guidelines" do not generally do that. For example, the second guideline gives no indication of how to minimize memory requirements. Many documents with guidelines do try to distinguish goals from guidelines (e.g., Toms and Williamson, 1998), but because it is not clear how to satisfy the guidelines, they are goals for all practical purposes.

This vagueness is a general problem with guidelines of this sort. On the one hand, many guidelines on HMD design simply identify desired properties of the system with little indication on how to achieve (or even measure) such properties. On the other hand, guidelines that do give specific advice (such as to avoid lists of more than seven items) are not generally true nor are broadly applicable across all situations.

There *are* some properties of cognition that are more universal, but the nature of these properties does not usually help guide system designs. For example, Tulving and Thompson (1973) proposed an encoding specificity principle of memory that states that the ability to remember an item depends on the similarity between the way the item is processed when it is encoded and the way it is processed when it is tested. There is substantial evidence that this statement is generally true for many different situations. However, this principle lacks sufficient detail to provide much guidance on how to design an HMD. In particular, one has to define how similarity is measured, but this term probably changes across individuals, tasks, and contexts.

We are not suggesting that the current use of guidelines is totally without merit. Although improperly named, guidelines do function as a set of goals for a design. Every design project needs goals of this type. Moreover, guidelines as they are currently used can push designers to consider issues that they might not have considered otherwise. Consider these two guidelines from Wickens et al. (1998):

1. Input modes, response devices, and tasks should be combined such that they are as dissimilar as possible in terms of processing stages, input modalities and processing codes.
2. The greater the automation of any particular task, the better the time-sharing capability. Information should be provided so that the person knows the importance of each task and therefore how to allocate resources between tasks.

These guidelines have many of the limitations and problems discussed above, but they do refer to specific topics in cognitive psychology that a designer might otherwise not consider. For example, the first guideline might motivate a designer to reconsider the system input modes and try to come up with a better approach. The guideline does not really indicate how this can be accomplished (or measured), but at least it does point to a potential need. In a similar way, a guideline that emphasizes limits to human memory may cause a designer to realize that users are struggling because of memory problems. In general, more thought given to the design process should lead to a better overall design.

Ultimately, a good design of a human-machine interface (HMI) system requires two things. First, the designer must be intimately aware of the needs and abilities of the user and must spend substantial time and effort to insure that the design satisfies those needs and takes advantage of those abilities. Second, the design must be tested, redesigned, and re-tested in a cycle that often repeats many times, taking as a criterion the final performance of the combined user/system in the test scenarios rather than simply the technical performance of the engineered system. Human factors (neuroergonomics) must be included at the beginning of a design process (e.g., Sheridan and Parasurman, 2006). Guidelines, in their current form, do not offer much meaningful guidance on how to accomplish these requirements.

## An alternative to guidelines

Rather than providing guidelines that do not actually offer guidance, we propose that it would be better to simply list the main properties of cognition that are likely to be important for HMI design. For example, it *is* important to know that human working memory has a limited capacity and that a design that expects too much from working memory is going to be problematic. Note that such a statement does not suggest any guidance on how to solve the problem; that is the job of the designer. In many respects, such a list may not be much different from the guidelines that currently exist. Nevertheless, we think that such a list would indicate that these issues are starting points for HMI design rather than guidance. This is an important distinction.

A more fundamental break from guidelines is to explore areas where quantitative theories and models of cognition can predict human behavior. A quantitative model of, say, stimulus visibility, can make a precise statement about the visibility of a stimulus and how visibility may change for a variety of situations. Thus, rather than telling a designer to consider the influence that other items' colors may have on the visibility of a target stimulus, a quantitative model can predict the effect of color variations.

When a quantitative model exists that can predict an aspect of human behavior that is important for HMD design (visibility, usability, memory, etc.), then there is a standard way of utilizing that model to guide the design process. Namely, one can use standard optimization approaches (hill-climbing, genetic algorithms, etc.) to build a variety of designs that are shaped or measured relative to the model-predicted human behavior. Such an optimization approach can also easily include multiple models that may focus on different aspects of the HMD design. Thus, part of the design process can be simulated on a computer, which leads to a savings in time and money by reducing the need for empirical measurements. Such simulations also free the designer to consider a wider variety of designs because details of the designs can be tested more quickly.

This approach has been successfully applied to several situations including multifunction displays (Francis and Rash, 2002), keyboard designs (Francis and Oxtoby, 2006; Francis and Rash, 2005; Li et al., 2006), and computer menus (Liu et al., 2002). The main limit of this approach is that current models of cognition are unable to accurately predict human behavior in the situations that are relevant to many HMI design projects (Rogers, 2004). In some cases the models cannot be applied to real-world situations because they make assumptions that cannot be satisfied. In other cases a model is simply wrong. However, as part of a larger program of modeling, identification of model limitations and mistakes can be used to promote model development; something that is quite difficult for a set of guidelines. We anticipate that a vigorous use of models of cognition would lead to dramatic refinement of models that would improve their ability to predict human behavior.

Perhaps the clearest lesson for HMD designers to appreciate about cognition is that all cognitive functions are context and task dependent. Thus there are few simple solutions to the complex demands of HMD design because so much of HMD use depends on the complex capabilities and limitations of cognition.

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